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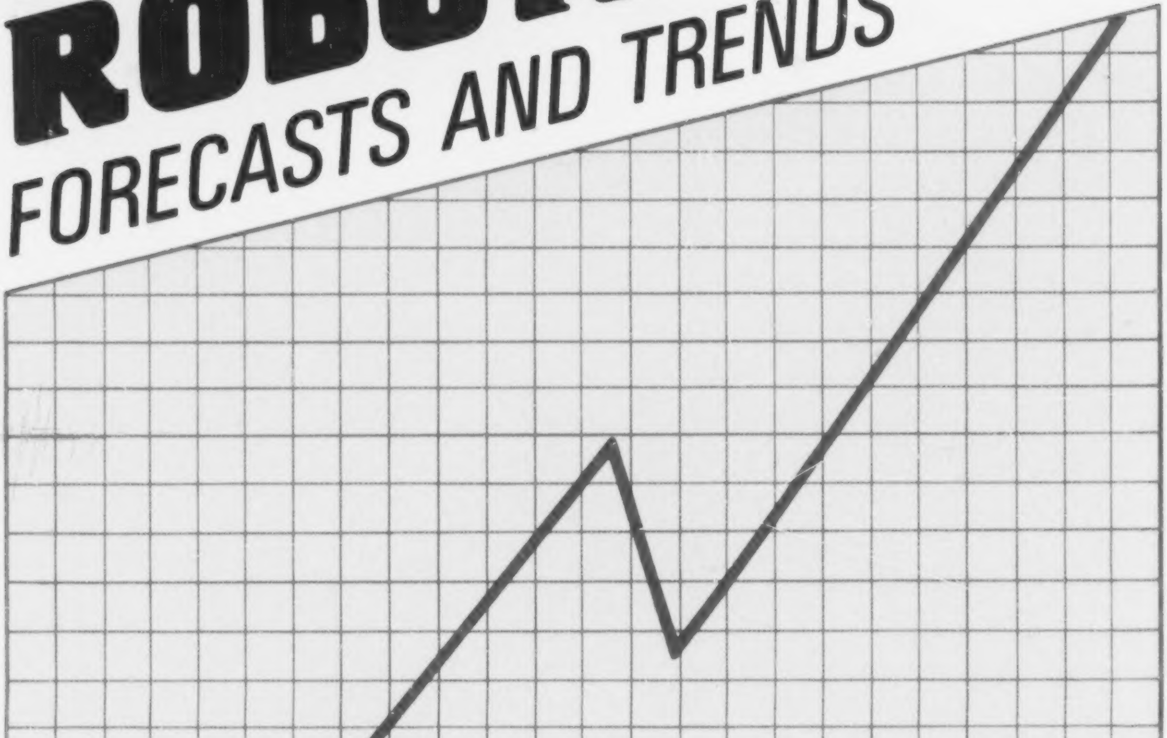
INDUSTRIAL ROBOTS

FORECASTS AND TRENDS



Delphi Study
Second Edition

Society of Manufacturing Engineers/The University of Michigan

INDUSTRIAL ROBOTS
FORECAST AND TRENDS

A Second Edition Delphi Study

Developed by the University of Michigan
with cooperation from the Society of Manufacturing Engineers

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INDUSTRIAL ROBOTS FORECAST AND TRENDS

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PREFACE

Industrial robots are fast becoming the hands and eyes of the production floor. The job of management, just as quickly, is becoming the monitoring and maintenance of information flow among distributed components of automated systems. As a key component of such systems, robots merit special attention. Current and future trends in their design, capability, and application serve as indicators of overall automation activity in the workplace.

Presented here is a comprehensive forecast of future trends in robotics through 1995 and, in some cases, through 2000. The survey project was conducted using the Delphi method (see Appendix B) over a period of four and one-half years. The results reflect the collective opinions of several hundred forecast panelists who are managers, engineers, and consultants employed by companies that use or produce robots, or that analyze industry developments.

This forecast is one of a series initiated in 1977 by the Society of Manufacturing Engineers and The University of Michigan. Past forecasts have concerned the outlook for material removal, manufacturing systems, assembly technology, and CAD/CAM. A future forecast on machine vision is planned.

The cooperation and persistence of many people are required for the completion of a useful Delphi forecast. This forecast on industrial robots is no exception. Many individuals unselfishly and graciously contributed substantial thought, time, and effort to this estimation of future trends. The authors especially wish to thank all of the panelists who devoted several hours of study and deliberation to their forecasts. Since the Delphi method involves anonymity of panelists, the authors are unable to personally thank each of them.

We would also like to recognize the excellent administrative support of Peter Blake and the reliable and efficient staff at SME. Several staff members of the Industrial Development Division deserve accolades. David J. Tucker assisted with data entry and analysis. Roger Guiles and David M. Peelle helped prepare the manuscript. Patricia G. Rapley and Aleda M. Thomas handled the typing.

Finally, recognition is due to R. William Taylor and William Hilty, past and present Executive Vice President and General Manager of SME, for their support and guidance during the forecasting process. On behalf of the users of these forecasts, the authors express appreciation to those who contributed so much.

Donald N. Smith

Peter Heytler, Jr.

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SECTION I

INTRODUCTION

Industrial robots have become increasingly commonplace in U.S. production facilities during the past 10 years. According to this forecast, robot unit and dollar sales will continue to grow throughout the coming decade.

The proliferation of programmable manipulators in factories, fields, and shops promises improved productivity and quality measures for companies that produce goods. It also is expected to spur changes in the nature of production employment and the educational attainments of members of the work force. As one indicator of the overall trend toward advanced automation systems in production, the increasing use of robots highlights larger shifts in markets, technology, and society.

Each of the three chapters of this research report focuses on one of these topics: General Trends (markets), Technology, and Sociology. Detailed data and comments, presented in Appendix A, offer further insight into expected patterns of robot use and their likely impacts on the U.S. economy.

Forecast History

This research project on future trends in industrial robot design, application, and social impact began in 1980 with an initial survey conducted by The University of Michigan and the Society of Manufacturing Engineers (SME). Preliminary results from the survey were published in 1982 in a research report entitled, Industrial Robots: A Delphi Forecast of Markets and Technology. The forecasting process continued, meanwhile, through the spring of 1985 and culminated in this report, which completes the project.

Several years were required to accomplish the current research because it was done using the Delphi forecasting method. The Delphi method presents a series of questionnaires to the same pool of expert panelists, with the expectation that a consensus forecast will be reached over several rounds of question repetition and refinement. With each new questionnaire, panelists are given a statistical summary of the results of the previous round along with written comments that support one individual's point of view or another's. An essential feature of the Delphi method is that all panelists remain anonymous participants in a group process. The final outcome is a set of results that represents the distilled knowledge of the entire group.

Forecast Procedures

Three panels were assembled to conduct the forecast, corresponding to the three topic areas explored. Panelists for General Trends and Technology forecasts, and some panelists for the Sociology forecast, were nominated to take part in the survey by the SME technical committee on robotics. Major trade unions representing manufacturing workers also nominated some members of the Sociology forecast panel. Each of the panels consisted of 60-100 persons.

To initiate the forecasting process, SME members were invited to submit questions for first-round questionnaires. More than 200 questions were submitted to the authors, who served as survey administrators. The questions were sorted by subject matter, edited into similar form, and mailed, in three separate questionnaires, to panelists. As responses to the three questionnaires were received, they were entered into their respective data bases. Some 30-60 panelists responded to each round of questionnaires. Three rounds were conducted in all.

Many forecast items gave target dates for a specific future development and asked panelists to project levels corresponding with target dates (e.g., total U.S. robot units in 1990, percentage distribution of number of axes among all robots sold in 1995, percentage of U.S. production workers actually displaced as a result of the installation of robots by industry in 1985). Other forecast items asked panelists to predict the date of a particular industry occurrence or to rank-order several future policy alternatives according to their projected industry impact. In a cover letter accompanying each questionnaire, panel members were encouraged not to forecast items outside the bounds of their personal expertise; consequently, the number of responses to any two items in any one round may have varied.

The standard statistical measures for summarizing and reporting the panels' responses to each question are the median and interquartile range (IQR). The median value is used because its computation is not sensitive to extremes in the distribution of responses. The IQR, specified by the middle 50 percent of the response distribution, indicates the data's central tendency. It therefore provides an indication of the level of consensus among panelists on any one item. A narrow IQR suggests relatively close agreement, while a broad range indicates divergent opinions.

Forecast Presentation

To facilitate review of the total forecast, responses have been organized by subject matter and comparisons made within each of these specialized topic areas. The sentence form used to describe future events has been revised from the interrogative form used in the panelists' questionnaires to a declarative statement for presentation in this report. Such editorial revisions were made with the awareness of the possibility of implying over-certainty which might inadvertently lead to misinterpretations of certain forecast events. To minimize such misunderstandings, the reader is urged to study the exact wording of pertinent questions in Appendix A--together with the accompanying response statistics and comments--and to relate each question to its corresponding statement in the narrative section of the report.

Forecast values given in the text of this report are the median responses of panelists. Letters and numbers preceding table headings or entries identify questions from which the data were developed. When evaluating data presented in the narrative section, turn to the corresponding questions in Appendix A and study the IQRs and written comments associated with each. They will provide an indication of the level of consensus on--or of group confidence in--a particular value.

Panelists' Characteristics

One-third of the panelists participating in this forecast hold management posts, as indicated in Table I-1. Twenty-eight percent are staff engineers with assignments in research and development, process planning, and material handling, etc. Twenty-seven percent of the panelists declined to give a job title on questionnaires. The remaining ten percent of the panelists represent various occupational classifications, including consultant, university professor, and research economist.

TABLE I-1

PERCENT OF PANELISTS BY JOB TITLE

Job Title	Percent
Manager/Director	34
Staff Engineer	28
Other (consultant, academic, etc.)	10
Unknown	27
Total	100*

*May not total 100% due to rounding.

Distribution of panelists by employer size is relatively even, as shown in Table I-2. Companies at the small end of the scale include consulting firms, robot component producers, and machine shops. Large companies represented by panelists include diversified multinational corporations and specialists in such industrial fields as automobiles, aircraft, agricultural and construction equipment, consumer appliances, defense weaponry, and electrical and electronic devices. The full range of industries represented by panelists, shown in Table I-3, indicates a relatively broad distribution of survey participation.

TABLE I-2

SIZE OF COMPANIES REPRESENTED BY PANELISTS

Employment Range	Percent
1 - 499	23
500 - 4,999	25
5,000 - 20,000	18
20,000+	23
Unknown	11
Total	100

TABLE I-3

INDUSTRIES REPRESENTED BY PANELISTS

Industry	Percent
Automotive/Truck	12
Electrical/Electronic Equipment	11
Aerospace	9
Research and Development	8
Defense	7
Basic Materials	7
Computers and Associated Equipment	6
Industrial Robots	6
Agricultural and Construction Equipment	4
Machine Tools	3
Other (e.g., Pharmaceuticals, Food, Telecommunications--also includes "unknown")	7
Total	100

While the data in Table I-3 suggest that some six percent of the panelists considered their companies to be in the industrial robot industry, responses presented in Table I-4 indicate that seventeen percent of the panelists represent companies that produce robots. The discrepancy between these two numbers may be explained by the fact that several large, diversified corporations represented by panelists produce robots, but do not consider their organizations to be specialists in the field; when asked to name their company's industry, they referred to its primary business field or declined to respond at all ("unknown").

TABLE I-4

ROBOT PRODUCTION AND USE BY PANELISTS' COMPANIES

"My company is:"	Percent
A User of Robots	75
A Manufacturer of Robots	17
Neither a User nor a Manufacturer (e.g., consultant)	8
Total	100

The panelists' characteristics given here describe the total pool of persons who returned filled-in questionnaires. To a large extent, they suggest that forecasts presented in this report reflect the distilled opinions and expectations of robot users across a broad spectrum of industrial classifications. However, since panelists were urged not to respond to questions outside the bounds of their personal expertise, the actual distribution of respondents vary from one forecast item to another. No single panelist responded to every questionnaire item in all rounds of the survey. In this sense, the panelists solely responsible for the data that yielded a particular forecast value are those who consider themselves to be experts on the topic in question.

Forecast Highlights

- Domestic sales of robots, now some 5,000 units annually, will reach 10,000 units by the end of the decade and 20,000 units by the end of the century, according to this forecast. Corresponding dollar sales projections, for robot units only, are $240 million in the current year, $516 million in 1990, and $637 million in 1995 (constant 1983 dollars).

- When the value of robots is added to other costs associated with their use--peripheral equipment and installation--the computer integrated manufacturing industry as a whole is expected to realize $471 million in sales this year, $1.2 billion in 1990, and $2.06 billion in 1995 (constant 1983 dollars).

- Actual numbers of robots purchased in the U.S. are expected to increase throughout the decade in all manufacturing classifications. The current leading consumer, the automotive industry, will account for a shrinking share of expanding total sales (51% now, 26% in 1995), as other indutries, particularly electronics and precision equipment producers (8% now, 16% in 1995) accelerate their pace of robot purchases.

- Robot leasing and time-share programming services are projected to develop into thriving commercial sectors; 15% of all robot units will be leased and a similar share programmed by time-sharing in 1995.

- The electronics industry is forecast to play a leading role in the application of robots to assembly tasks, accounting for 14% of all unit sales in 1995. Assembly applications in all other industries, meanwhile, are expected to grow in parallel, explaining 12% of robot sales in 1995. Thus, in ten years, roughly one-quarter of all new installations is projected to be in assembly.

- Industrial robots are forecast to change in appearance, improve in accuracy, and become available in abundant variety. By 1995, for example, 15% will have two or more arms, 11% will be mounted on ceilings or walls; 21% will move along a track; computer control devices (micro, mini, or mainframe) will direct the movements of 90% of all robots; and certain classes of robots will be accurate to ± .0005 inches per second.

- Half of all robots that are controlled by computers are expected to be programmed off-line by 1995; some 40% will be debugged by CAD simulation. The odds of a standardized off-line robot programming language being in use during this period was rated 25% (or 1:4).
- Sensory devices will be utilized by 60% of all robots by 1995, according to this forecast. They will be most plentiful on robots devoted to inspection, assembly, and welding tasks. Among robots with some form of sensing capability, one-quarter will have machine vision, one-quarter tactile sensors, another quarter some other kind of sensor (e.g., range, proximity), and the balance will be equipped with two or more sensor types.
- The U.S. manufacture of robots is expected to create a total of more than 44,500 jobs by 1995. Some 3,000 workers will be employed by robot producers, 4,500 in supplier industries, another 25,000 will perform maintenance in robotized facilities, and about 12,000 programmers will create and maintain robot software.
- Throughout industry, the overall displacement rate of workers by robots is forecast to reach 4.3% by 1995. In some industries as many as 20% of the current work force may be displaced by robots, but within this group of affected workers, just 5-6% will actually be disemployed.
- Nearly 90% of displaced workers will remain with their current employers through lateral transfer, retraining, or promotion. Among the remainder, half will take early retirement and half will be terminated.

- According to forecast estimates, 10% of those disemployed by technological change will find new jobs in 2 months or less, 37% within 6 months, and 73% within a year. Some 7% (or about 1,000 people per year through 1990) will be unable to find alternative employment due to lack of marketable skills.

- The impact of robot installations on workers is expected to be greatest in automotive and electronics industries through 1990, with mounting impact thereafter in consumer non-durables (e.g., food, textiles), primary metals, fabricated metal products, and aerospace industries.

- Occupations most affected by robot installations are expected to include production painters (20% displacement), welders and flamecutters (20%), machinists and machinery operators (13%), and assembly workers (10%). Line supervisory personnel are projected to decline by 3%.

- Increasing automation of production is forecast to create a need for a more highly trained labor force; entry level jobs "with no training or experience necessary" will become increasingly rare. This is expected to result in a decrease in the high school drop-out rate (20% now, 13% in 1995). More young people will enter the work force having completed technical school or some college education (32% now, 38% in 1995).

- Private industry is expected to bear the brunt of retraining costs for displaced workers (65-70% throughout) with some increases forecast in training programs offered by state and local governments (6% now, 9% in 1995). Retraining provisions are expected to become increasingly prevalent in union-management contracts, and it is likely to become the norm for management to provide early warning of impending technological change in the workplace.

- Panelists rated the following prospective government actions as potentially useful in the transition to advanced automation in production facilities: direct funding and promotion of research and development; relaxation of antitrust laws to permit joint corporate research and development; accelerated depreciation for robotic equipment; government-sponsored low-interest loans for purchases of automation equipment; and increases in secondary and college-level educational expenditures.

- Regional activity in the design, development, and manufacture of robots is expected to mirror market activity. The East North Central states, home of the automotive industry, are expected to play a continuing leadership role in robotics (40% of firms now, 28% in 1995). Pacific states, the epicenter of electronic production, are projected to gain a substantial share of robot producers (12% now, 17% in 1995). Other regions are expected to realize small increases (1-2%) in the local concentration of robot firms as markets diffuse through industry.

SECTION II

GENERAL TRENDS

Market Characteristics

At the beginning of the 1980s, plant automation in general, and robotics in particular, were viewed as potentially the most revolutionary developments in manufacturing since the mass production lines of Henry Ford. It was felt by many that robotics held the key to vastly improved productivity and quality control, a panacea which would revitalize American industry. In the 1981 Delphi survey of robotics, as well as in numerous other studies, this unrestrained optimism in the supposedly limitless potential of robotics, coupled with the belief that the relatively severe recession of 1979-80 had given way to a prolonged period of economic expansion, led to predictions of enormous growth (35-40 percent per year) in the sales levels of robotic equipment over the remainder of the decade.

Unfortunately, year-end 1981 marked the beginning of what has been called the worst recession since the Great Depression of the 1930s. Sales of all capital equipment fell sharply, immediately rendering the rosy view of the growth in the robotics industry obsolete. By 1984, when this Delphi II survey was conducted, a new, more vigorous recovery had established itself, and confidence in the promise of advanced production technology returned, although on a much more cautious note (Table II-1). The earlier 35% annual growth rates have been replaced with more conservative, but still impressive, 20% per year estimates. This reduction may be due in part to lingering concerns over federal budget problems and the attendant potential for another economic downturn.

TABLE II-1

Forecast of Sales of Robots in the U.S.
(Thousand of Units)

	1984 Forecast		1981 Forecast	
Year	Unit Sales	Annual Growth Rate	Unit Sales	Annual Growth Rate
1981	---	--	2,300	--
1982	---	--	3,000	30.4%
1983	---	--	4,300	43.3
1984	4,200*	--	6,000	39.5
1985	5,000	19.0%	8,000	33.3
1986	6,000	20.0	---	--
1987	7,000	16.7	---	--
1988	8,200	17.1	---	--
1989	9,500	15.9	---	--
1990	11,000	15.8	---	--
1995	15,000	6.4	---	--
2000	20,000	5.9	---	--

*Actual year-end 1984 figure.

The forecast of future robot sales by industrial sector emphasizes the increasingly widespread acceptance of robots in virtually all sectors of the economy (Table II-2). Although the automotive industry is expected to continue to account for the majority of purchases in 1985, most other industries will account for significant portions of the robot market by 1995. Key among these is expected to be the electronics and precision equipment industry. From 1985 to 1995, this sector is expected to double its market share, from 8% (or approximately 400 units purchased) to 16% (2,400 units). Other significant gains are forecast to be made by the machinery manufacturing industry, from 8% (400 units) to 11% (1,650 units) by 1995; the aerospace industry, from 6% (300 units) to 8% (1,200 units); and the non-metal primary commodities and consumer non-durables industries. Most other industries are predicted to pick up from 1 to 2 percentage points during the same ten-year period.

TABLE II-2

(G-3) Percentage Distribution of Robot Sales in the U.S., by Industry

	1985	1990	1995
Agriculture	1%	1%	1%
Mining and extractive	1	2	2
Construction	0	1	1
Electricity generation	1	1	1
Consumer non-durables	2	5	5
Non-metal primary commodities	2	4	5
Primary metals	3	4	5
Non-metal fabricated commodities	5	6	6
Fabricated metal products	10	8	8
Machinery	8	10	11
Electronics/precision equipment	8	10	16
Automotive	51	38	26
Aerospace	6	6	8
Other transport equipment	2	3	4
	100%*	100%*	100%*

*May not total 100% due to rounding.

Because of this rapid growth in the rate of purchases of robots throughout American manufacturing, two sectors will decline in their relative shares of the market, although both will still experience growth in their absolute numbers of robots purchased. These two industries include the automotive sector, from a 51% market share in 1985 (2,550 units) to only 26% (3,900 units) in 1995; and the fabricated metal products sector, from 10% (500 units) in 1985 to 8% (1,200 units) in 1995.

Panelists were also asked to forecast robot sales by application (Table II-3). As technology improves the accuracies and repeatabilities available to end-users, more precise and delicate operations will become feasible. As a direct result, the fastest growing applications will involve assembly operations, both in the electronics industry (from 6% of sales in 1985 to 14% in 1995) for the manufacture of small components, and in the remainder of industry in general (from 5% to 12%). Inspection units will also double its market share (from 5% to 10%) during this period, owing mainly to improved sensors and the advent of better real-time processors.

TABLE II-3

(G-2) Percentage Distribution of Robot Sales in the U.S., by Robot Application

	1985	1990	1995
Machine tending	16%	15%	15%
Material transfer (excl. machine tending)	16	15	15
Spot welding	26	15	10
Arc welding	10	10	9
Spray painting/coating	10	10	7
Processing*	5	7	7
Electronics assembly	6	12	14
Other assembly	5	8	12
Inspection	5	7	10
Other	1	1	1
	100%	100%	100%

*Includes such applications as routing, drilling, grinding, etc.

At the other end of the scale, the percentage of robots sold for spot welding applications is forecast to drop sharply, from 26% in 1985 to 10% by 1995. This event is a direct reflection of the decline of sales of these units to the automotive industry, by far the major purchasers of welding robots. This also accounts for the non-growth in the arc-welding market share; despite the anticipated developments in seam-tracking sensor technology critical to the implementation of these units, the biggest potential user will have reduced its demand for welding robots.

The biggest sector of the applications market will remain those units used to handle materials, whether for the loading and unloading of machine tools, or to transfer materials from one location to another. Combined, these robots will account for roughly one-third of unit sales over the forecast period.

TABLE II-4

(G-10c) Geographical Distribution of Robots in the U.S.

	1985	1990	1995
New England	10%	11%	11%
Mid-Atlantic	10	11	10
South Atlantic	8	9	9
East North Central	40	34	28
West North Central	5	5	6
East South Central	5	5	6
West South Central	5	5	7
Mountain	5	5	6
Pacific	12	15	17
	100%	100%	100%

Another topic of interest is the geographical distribution of robots within the U.S. over the next decade (Table II-4). Not unexpectedly, the Midwest region (encompassing Ohio, Michigan, Indiana, Illinois, and Wisconsin) is seen as having the lion's share of all robots in place throughout the forecast period. However, there are several interesting trends to be observed. The most obvious is the sharp decline in the percentage of robots situated in the Midwest region, from 40% in 1985 to "only" 28% by 1995. This prediction is readily understandable when the relative decline in the market share represented by the automotive industry is considered. Conversely, the significant rise in the percentage of robots in the Pacific region can be tied to the emerging prominence in the use of robots by the electronics and, to some extent, aerospace industries associated with that region. However, in light of this latter observation, it remains somewhat puzzling as to why a similar phenomenon is not expected to occur in New England, with its similar industrial mix; instead, its share of installed robots is forecast to remain virtually constant. The same is also expected to be true in the other areas of the United States.

TABLE II-5

(G-4) Average Price of New Robot, by Type of Application
(In Constant 1983 Dollars)

	1985	1990	1995
Machine tending	$35*	$37*	$31*
Material transfer (excl. machine tending)	36	38	35
Spot welding	60	58	50
Arc welding	60	60	58
Spray painting/coating	60	60	60
Processing	45	50	59
Electronics assembly	35	40	31.6
Other assembly	35	35	35
Inspection	52	50	50
Other	40	38	40

*Thousands of 1983 dollars.

Delphi panelists were asked several questions regarding the costs associated with the implementation of robots and robotic systems. Among these was an inquiry on average prices of the robots themselves, by type of application, and expressed in constant 1983 U.S. dollars (Table II-5). These prices refer strictly to the robot and any standard tooling, and specifically exclude optional ancillary equipment. For 1985, panelists anticipated prices to range from a low of $35,000 (assembly and material transfer units) to a high of $60,000 (welding, spray coating). In ten years, despite the advances in technological complexity and capabilities of new robots, the price range is expected to decline slightly, from a low of $31,000 (material transfer) to a high of $58,000 (arc welding) to $60,000 (spray coating).

By applying these average prices to the unit sales by application shown in Table II-3, the dollar volume of sales for the entire domestic U.S. robot industry can be estimated (Table II-6). The 1985 figure is expected to be approximately $240 million; by 1990, it will have more than doubled to around $516 million (all dollar figures expressed in constant 1983 dollars). The predicted slowdown in sales after 1990 will result in a more gradual expansion to $637 million by year-end 1995.

TABLE II-6

Forecast of Dollar Sales of Robots in the U.S., by Application
(In Millions of 1983 Dollars)

	1985		1990		1995	
	Unit Sales	Total $ (mil.)	Unit Sales	Total $ (mil.)	Unit Sales	Total $ (mil.)
Machine tending	800	28.0	1,650	61.1	2,250	69.8
Material transfer	800	28.8	1,650	62.7	2,250	78.8
Spot welding	1,300	78.0	1,650	95.7	1,500	75.0
Arc welding	500	30.0	1,100	66.0	1,350	78.3
Spray painting	500	30.0	1,100	66.0	1,050	63.0
Processing	250	11.3	770	38.5	1,050	62.0
Electronics ass'y.	300	10.5	1,320	52.8	2,100	66.4
Other assembly	250	8.8	880	30.8	1,800	63.0
Inspection	250	13.0	770	38.5	1,500	75.0
Other	50	2.0	110	4.2	150	6.0
Totals	5,000	$240.4	11,000	$516.3	15,000	$637.3

Robots as Part of CIM

With the exception of the installations within the automotive industry, the majority of robot purchases in the U.S. to date have been for stand-alone applications rather than as part of integrated systems (Table II-7). While there have been several widely cited reasons for this, including high up-front costs for entire systems and long paybacks reported by some installations, the primary one is unfamiliarity with this complex new technology. By investing first in limited robotic stations for specific applications, users can gradually become familiar with the capabilities of robots before moving on to invest in more comprehensive systems. As users move up the experience curve, ancillary equipment needed to complete CAD/CAM or CIM systems can be purchased, or the current set-up can eventually be replaced by more advanced technologies. This long-range trend toward more complex systems is apparent in Table II-7. In 1985, 60% of all robots sold are expected to be for stand-alone applications; by 1995, this figure will only be 30%.

TABLE II-7

(G-5a) Percent of Robots Sold as Stand-alone Units, Versus Units Incorporated into Manufacturing Systems

	1985	1990	1995
Stand-alone units	60%	50%	30%
Part of system/cell	40	50	70
	100%	100%	100%

In order to get a more detailed picture of the entire robot/CIM industry sales, Delphi respondents were asked to estimate the percentage of the installed system cost represented by the robotic component (Tables II-8 and II-10). Questions regarding the costs associated with the planning, installation, and integration of robot-equipped CIM systems into the production facility, again expressed as a percent of robot cost, were also included (Table II-9).

At present, most of the recent CIM purchases have tended to be small and comparatively uncomplicated, with the robot itself representing about half the total purchase price. However, as users become more familiar with the technology and potential of more extensive automated production systems, the percentage of total cost represented by robots will decline.

Using the data in the above tables, it is now possible to derive an estimate of the size (on a dollar volume basis) of the entire robot-equipped CIM industry. As the calculations in Table II-10 indicate, this industry will mushroom from a current figure in the neighborhood of $470 million to over $2 billion by 1995 (in 1983 dollars) for all aspects of the robotics industry, including all robots, ancillary equipment, and planning and installation. These figures are much reduced from estimates circulated at the beginning of the decade, estimates often ranging from $1.2 billion to $1.5 billion for robots alone by 1990.

TABLE II-8

(G-5b) Percent of Total System Value Represented by Robot

	1985	1990	1995
Machine tending	50%	40%	40%
Material transfer	50	50	50
Spot welding	50	40	41
Arc welding	50	50	45
Spray painting/coating	60	60	60
Processing	40	35	40
Electronics assembly	30	33	34
Other assembly	35	30	30
Inspection	45	40	38
Other	50	35	30

TABLE II-9

(G-5c) Initial Costs Associated with the Planning, Installation, and Integration of Robot into Facility, Expressed as Percentage of Actual Robot Cost

1985	1990	1995
40%	35%	30%

TABLE II-10

Calculations of the Size of Domestic Robot-Equipped CIM Industry*

	1985	1990	1995
Total robot $ sales	$ 240.4	$ 516.3	$ 637.3
Percent of robots used in cells	x .40	x .50	x .70
Value of robots in cells	$ 96.2	$ 258.2	$ 446.1
Value of remainder of cell equipment, expressed as a multiple of robot value	x 1.00	x 1.50	x 2.13
Value of non-robot cell equipment	$ 96.2	$ 387.3	$ 948.0
Total robot sales	$ 240.4	$ 516.3	$ 637.3
Value of other cell equipment	$ 96.2	$ 387.3	$ 948.0
Total value of equipment	$ 336.6	$ 903.6	$ 1585.3
Installation costs, expressed as fraction of system value	x .40	x .35	x .30
Total installation costs	$ 134.6	$ 316.3	$ 475.6
Total value of all robots	$ 240.4	$ 516.3	$ 637.3
Total value of non-robotic cell equipment	$ 96.2	$ 387.3	$ 948.0
Total installation costs	$ 134.6	$ 316.3	$ 475.6
Total Spent on New CIM Equipment	$ 471.2	$1219.9	$2060.9

*All amounts in millions of constant 1983 U.S. dollars.

Figures supplied by the Delphi panelists were specifically requested to be in constant 1983 dollars. Other forecasts regarding the U.S. economy indicate relatively low amounts of inflation for the remainder of the decade, probably averaging approximately 6% per year. Applying this average inflation rate to the constant-dollar forecasts supplied above, the actual 1990 dollar sales forecast for robots and equipment comes to well over $1.8 billion by 1990. Thus, although it has been reduced from earlier, more optimistic levels, this new Delphi II forecast still depicts a generous high-technology growth sector for U.S. producers and vendors of robots.

Economic Justification

After-tax payback periods for robots are forecast to be about three years in the near future for most applications, dropping to between two and two and a half years for many by 1995 (Table II-11). This is in contrast to predictions of two years for most types of robots by 1985 provided in the earlier Delphi forecast. One potential explanation for this change is perhaps a lower expectation for indirect savings associated with robots, although this is a matter of conjecture.

TABLE II-11

(G-12) Average After-tax Payback Period (In Years)
Experienced by Robot Users, by Type of Robot

	1985	1990	1995
Machine tending	3.0	2.5	3.0
Material transfer	3.0	2.5	2.5
Spot welding	2.5	2.3	2.1
Arc welding	2.5	2.3	2.5
Spray painting/coating	3.0	2.5	2.1
Processing (routing, drilling grinding, etc.)	3.0	3.0	3.0
Electronics assembly	3.0	3.0	3.0
Other assembly	3.0	3.0	3.0
Inspection	3.0	2.5	2.5
Other	3.0	3.0	2.5

When asked to categorize the nature of gains made through the use of robotic equipment, the direct replacement of labor accounted for over half in most applications (Table II-12). The highest values were found in such traditionally labor-intensive areas as material handling and welding. This economic aspect is more fully discussed in the Sociology section. The second largest area of savings is the increase in product quality (Table II-13). The values for these gains vary rather greatly, from lows in the single digits to highs representing over one-third of the total savings attributable to the use of robots. Usually, the savings are derived from increased precision; thus, these are greatest in such applications as electronic assembly, inspection, and welding.

TABLE II-12

(S-27) Percent of All Production Savings Represented by Direct Labor Replacement, by Robot Application

	1985	1990	1995
Machine tending	93%	86%	74%
Material transfer	56	56	55
Spot welding	50	58	60
Arc welding	62	58	54
Spray painting/coating	40	38	34
Processing (routing, drilling grinding, etc.)	50	50	50
Electronics assembly	38	40	41
Other assembly	41	44	47
Inspection	55	51	46

There were several other categories of potential savings presented to panelists. Tables II-14 through II-22 summarize the complete breakdown of savings by robot application. Aside from savings resulting from labor cost reduction and increased product quality, the most significant remaining sources frequently mentioned include a decrease in wastage of materials, a reduction in inventory required to be stored, and worker safety. On the issue of worker safety, the 1981 Delphi I study forecast a 30% reduction in factory accidents by 1995, resulting directly from the increased use of robots.

TABLE II-13

(S-27) Percent of All Production Savings Represented by Product Quality Gains, by Robot Application

	1985	1990	1995
Machine tending	6%	9%	15%
Material transfer	6	8	12
Spot welding	32	24	18
Arc welding	15	24	27
Spray painting/coating	34	32	28
Processing (routing, drilling grinding, etc.)	18	19	21
Electronics assembly	38	34	32
Other assembly	26	21	13
Inspection	36	38	38

TABLE II-14

(S-27a) Percentage Breakdown of Total Savings Associated with Material Transfer Robots

	1985	1990	1995
Product quality	6%	8%	12%
Direct labor productivity	56	56	55
Indirect labor productivity	11	12	12
Energy savings	1	2	2
Material waste reduction	6	6	6
Less floor space	2	1	0
Inventory reduction	9	8	6
Simplified management	3	1	1
Worker safety	6	6	6
Other	0	0	0
	100%	100%	100%

TABLE II-15

(S-27b) Percentage Breakdown of Total Savings Associated with Spot Welding Robots

	1985	1990	1995
Product quality	32%	24%	18%
Direct labor productivity	50	58	60
Indirect labor productivity	6	6	6
Energy savings	0	0	0
Material waste reduction	6	6	6
Less floor space	0	0	0
Inventory reduction	6	6	10
Simplified management	0	0	0
Worker safety	0	0	0
Other	0	0	0
	100%	100%	100%

TABLE II-16

(S-27c) Percentage Breakdown of Total Savings Associated with Arc Welding Robots

	1985	1990	1995
Product quality	15%	24%	27%
Direct labor productivity	62	58	54
Indirect labor productivity	8	6	5
Energy savings	0	0	0
Material waste reduction	8	6	5
Less floor space	0	0	0
Inventory reduction	7	6	9
Simplified management	0	0	0
Worker safety	0	0	0
Other	0	0	0
	100%	100%	100%

TABLE II-17

(S-27d) Percentage Breakdown of Total Savings Associated with Spray Painting Robots

	1985	1990	1995
Product quality	34%	32%	28%
Direct labor productivity	40	38	34
Indirect labor productivity	6	6	6
Energy savings	2	0	6
Material waste reduction	11	11	11
Less floor space	0	0	0
Inventory reduction	1	7	9
Simplified management	0	0	0
Worker safety	6	6	6
Other	0	0	0
	100%	100%	100%

TABLE II-18

(S-27e) Percentage Breakdown of Total Savings Associated with Processing (e.g., Routing, Grinding, Drilling, etc.) Robots

	1985	1990	1995
Product quality	18%	19%	21%
Direct labor productivity	50	50	50
Indirect labor productivity	6	6	7
Energy savings	2	3	3
Material waste reduction	12	10	7
Less floor space	0	0	0
Inventory reduction	6	6	6
Simplified management	0	0	0
Worker safety	6	6	6
Other	0	0	0
	100%	100%	100%

TABLE II-19

(S-27f) Percentage Breakdown of Total Savings Associated with Electronics Assembly Robots

	1985	1990	1995
Product quality	38%	34%	32%
Direct labor productivity	38	40	41
Indirect labor productivity	6	5	5
Energy savings	0	0	0
Material waste reduction	6	11	11
Less floor space	0	0	0
Inventory reduction	6	5	5
Simplified management	6	5	5
Worker safety	0	0	1
Other	0	0	0
	100%	100%	100%

TABLE II-20

(S-27g) Percentage Breakdown of Total Savings Associated with Other Assembly Robots

	1985	1990	1995
Product quality	26%	21%	13%
Direct labor productivity	41	44	47
Indirect labor productivity	13	13	13
Energy savings	0	0	0
Material waste reduction	5	5	7
Less floor space	0	0	0
Inventory reduction	6	9	13
Simplified management	6	5	4
Worker safety	3	3	3
Other	0	0	0
	100%	100%	100%

TABLE II-21

(S-27h) Percentage Breakdown of Total Savings Associated with Inspection Robots

	1985	1990	1995
Product quality	36%	38%	38%
Direct labor productivity	55	51	46
Indirect labor productivity	9	7	8
Energy savings	0	0	0
Material waste reduction	0	4	8
Less floor space	0	0	0
Inventory reduction	0	0	0
Simplified management	0	0	0
Worker safety	0	0	0
Other	0	0	0
	100%	100%	100%

TABLE II-22

(S-27i) Percentage Breakdown of Total Savings Associated with Machine Tending Robots

	1985	1990	1995
Product quality	6%	9%	15%
Direct labor productivity	93	86	74
Indirect labor productivity	1	1	1
Energy savings	0	0	0
Material waste reduction	0	0	0
Less floor space	0	0	0
Inventory reduction	0	4	10
Simplified management	0	0	0
Worker safety	0	0	0
Other	0	0	0
	100%	100%	100%

Vendor Characteristics

Presently, nearly two-thirds of robot purchases are made by the end users directly from the robot manufacturers. (Table II-23). This is primarily a reflection of the general lack of expertise with these systems among purchasers, as well as a low number of experienced vendors, resulting in heavy dependence upon the manufacturers. However, by 1995, this fraction will be reduced substantially, to just over half of all sales. Increasing their market share will be independent systems houses. These vendors not only will sell "off-the-shelf" robots and equipment to end-users, but also will be able to custom-design robotic systems from components for specific applications and users.

TABLE II-23

(G-6) Distribution of Robot Sales by Source Type

	1985	1990	1995
Robot manufacturers	63%	55%	53%
Licensed distributors	26	30	26
Systems houses	11	15	21
	100%	100%	100%

TABLE II-24

(G-7) Sales of Total "Turn-key" Packages Versus Robot Alone

	1985	1990	1995
Total "turn-key" package	40%	50%	50%
Robot alone	60	50	50
	100%	100%	100%

Reflecting the anticipated growing trend toward the utilization of entire systems, panelists project that purchases of complete "turn-key" packages will increase from 40% of all domestic robot sales in 1985 to 50% by 1990 and 1995 (Table II-24). This is most likely due to the comparative ease in the installation of a stand-alone robot relative to an entire CAD/CAM or CIM system. Supporting this view are the data in Table II-7, in which the proportion of stand-alone sales to system sales for 1985 and 1990 is identical to that of non-"turn-key" installations relative to all purchases.

The Delphi panelists were also asked to consider other robot-related services that might become available to users over the next ten years. One commonly raised possibility is robot leasing. Rather than invest large sums of money in a new and unfamiliar technology, companies could lease robots in order to become familiar with their capabilities and ultimately develop an optimal production strategy before actually purchasing the requisite equipment. Although still rather small, the leasing business could involve as much as 15% of all robots in operation by 1995 (Table II-25).

TABLE II-25

(G-20b) Leased Robots, as a Percent of all Robots in Operation

	1985	1990	1995
Percent of all robots	5%	10%	15%

Another possibility is the use of commercial computer time-sharing services and software packages to program computers to operate robotic facilities (Table II-26). Again, the percentage of robots tied into such services is anticipated to be relatively small (15% of all units by 1995), but significant.

TABLE II-26

(G-20a) Robots Tied into Commercial Computer Time-Sharing Services

	1985	1990	1995
Percent of all robots	5%	10%	15%

Imports vs. Exports

As with many commodities in today's economy, the subject of international trade in robotics is being hotly debated around the country. Already, large numbers of robots are being imported into the U.S. from Japan and Western Europe, while exports have lagged. This trend is viewed by the panelists as continuing well into the 1990s, with two of every five robots sold in this country being imported (Table II-27). While some new countries, notably Korea, may begin to penetrate the domestic market (Table II-28), Japan and Western Europe will remain the overwhelmingly dominant exporters to the U.S. Interestingly, there will be a gradual shift away from Japanese units toward those of Western Europe. However, the Japanese will probably continue to dominate the market at the lower end, whereas European sales will probably consist of higher-technology, more complex units.

TABLE II-27

(G-8a) Domestic Purchases of Foreign-Built Versus U.S.-Built Robots

	1985	1990	1995
Foreign-built	37%	40%	40%
U.S.-built	63	60	60
	100%	100%	100%

TABLE II-28

(G-8b) Country of Origin of Imported Robots

	1985	1990	1995
Japan	69%	61%	54%
Western Europe	28	31	33
Korea	0	2	3
Other Asia	0	0	1
Australia	0	0	0
Canada	0	0	0
All other foreign	3	6	9
	100%	100%	100%

This raises questions regarding the appeal of foreign robots as opposed to domestically-produced units, especially in the face of glowing tributes to American technology and inventiveness in the field of automation (Table II-29). When asked about this, the panelists responded very strongly that there were two basic reasons: price and performance. Further, the respondents foresaw little likelihood of these advantages enjoyed by foreign producers changing over the near future. A third factor, robot design, was also ranked highly by many panelists; the remainder of the suggested reasons met with very mixed responses.

This strong combination of features (low cost, high performance, good design) suggests that the typical Japanese robot is what most panelists had in mind when they listed the foreign producer advantages. More specifically, respondents likely envisaged a comparatively uncomplex unit capable of only limited applications (but very capable when employed for those uses), and thus relatively inexpensive to manufacture. Also, the simplicity of design leaves fewer opportunities for malfunctions, and easier repair when problems do arise. This view helps to explain the seemingly contradictory responses of the panelists when asked to comment on U.S. robot exports.

TABLE II-29

(G-10a) Rank-order of Importance of Following Factors in the Decision by U.S. Users to Buy Foreign-Built Robots

	1985	1990	1995
Purchase cost advantage	1	1	1
Performance	2	2	2
Robot design features	3	3	3
Superior maintenance	4	4	4
Superior delivery	5	5	5
Better warranties	6	6	6
Favorable finance terms	7	7	7
Other	8	8	8

According to a report by the U.S. International Trade Commission issued in 1982, total domestic robot exports came to about 117% of imports; i.e., a favorable trade balance. However, although no figures for 1984 were available at the time of this study, it is widely believed that worldwide economic conditions have caused this figure to drop considerably. By 1985, according to the panelists, the ratio will have fallen to 100%, or one robot imported for every robot exported; and by the 1990s, it will have fallen still further, all the way to 90%, a significant slippage (Table II-30).

TABLE II-30

(G-9a) Ratio of U.S. Robot Exports-to-Imports

	1985	1990	1995
Exports-to-imports	100%	90%	90%

As with robot imports, the reasons behind foreign purchases of U.S.-built robots were examined (Table II-31). Somewhat surprisingly, the top three reasons were the same as for domestic purchases of foreign-built units. The big difference was in the rank order. The main attractions of robots manufactured in the U.S. were their technological characteristics: performance and design. Price came in a distinct third. This indicates that the typical robot exported from the U.S. is expected to be technologically more complex and capable of a wider variety of tasks. It also means a higher price tag. As there has been a noticeable trend toward the use of more simple, "dedicated" robots in industrial settings worldwide, it is therefore not surprising that the Japanese models will experience a higher demand on a unit basis. Unless U.S. manufacturers respond more vigorously to this trend (and the world economic situation settles), the slide in the export/import ratio can be expected to continue.

TABLE II-31

(G-10b) Rank-order of Importance of Following Factors in the Decision by Foreign Users to Buy U.S.-Built Robots

	1985	1990	1995
Performance	2	1	1
Robot design features	1	2	2
Purchase cost advantage	3	3	3
Superior maintenance	4	4	4
Superior delivery	7	5	5
Better warranties	5	6	6
Favorable finance terms	6	7	7
Other	8	8	8

The Role of Government

One lengthy question in the study focused exclusively on the potential role of the federal government to encourage growth in the robotics and automation industry. Panelists were supplied with lists of 15 possible government actions, and asked to rate each action individually as to its degree of usefulness in the promotion of the industry. Somewhat surprisingly, there appears to be a rather exceptional amount of interest in the potential for federal governmental action (Table II-32). While no course mentioned received a "1" (indicating extreme usefulness), neither did any receive a "5" (no usefulness at all). But there were quite a few "2"s and "3"s, while the interquartile ranges revealed more sentiment for government actions than against.

Potential programs which met with the greatest interest were mainly those involving indirect measures. These included the promotion of greater research and development efforts, both via increased direct funding and the reduction of antitrust barriers to joint corporate R & D projects; various incentives for investors in automation equipment, such as accelerated depreciation allowances, direct tax breaks, and government-sponsored low-interest loans for the purchase of equipment; and an increase in secondary school and college-level educational expenditures. At the other end of the scale were more potentially interventionist activities, such as a government-operated robot leasing program; the creation of a federal Industrial Policy Agency; government purchases of automation equipment to help shore up demand; and the adoption of trade protectionist measures to stem the influx of robots from other countries (although export subsidies were of higher interest).

TABLE II-32

(G-13) Rank (from 1 to 5) the Degree of Usefulness of Positive Federal Government Action on Each of the Following Issues

	Degree of Usefulness[1]
Direct funding and promotion of research and development	2
Relaxation of antitrust laws to permit joint corporate research and development	2
Accelerated depreciation for robotic equipment	2
Direct tax breaks for robot purchasers	2
Government-sponsored low-interest loans to potential robotics or other automation purchasers	2
Increase in secondary and college-level educational expenditures	2
Government robotic information clearinghouse and/or data bank	3
Export subsidies or other benefits	3
Establishment of government retraining programs for displaced workers	3
Special programs to assist small suppliers to the robotics industry in obtaining financial backing	3
Reestablishment of the Nixon Administration's National Productivity Center to conduct research into productivity enhancement	3
Development of government-sponsored robot leasing program	4
Establishment of an industrial policy agency	4
Federal government procurement of newly-introduced robot products to reinforce initial demand	4
Trade protection measures on behalf of the robotics industry	4

*1 = very useful; 5 = not at all useful.

Obstacles to Robot Implementation

The Delphi panelists were asked to comment on the present shortcomings of robots in the workplace. When presented with a list of six commonly cited criteria for robot performance, and requested to rank them as constraints to the wider implementation of robots, there was a great deal of uniformity in the responses (Table II-33). Repeatability and accuracy were the major concerns of the panelists, while, somewhat surprisingly, velocity was well down on the list, trailing up-time and load capacity.

TABLE II-33

(G-15) Rank-ordering of Current Performance Constraints to the Wider Implementation of Robots

	1985 Rank
Repeatability	1
Accuracy	2
Up-time	3
Load Capacity	4
Velocity	5
Size of Robot	6

Respondents were also asked to comment on the degree of severity of various shortcomings in robotic hardware (Table II-34). While most items on the list were considered to be of moderate importance, only two approached critical: inadequate non-vision sensors, and stronger, lighter robot arms. As might be expected, these are two major areas of current robotics research in the U.S.

TABLE II-34

(G-22) Degree of Severity of Current Voids in Robot Hardware (1 = critical; 5 = not important)

Void in Robotic Hardware	Degree of Importance
Inadequate non-vision sensors	2
Stronger, lighter arm	2
Arm oscillations/damping	3
Extended reach	3
Gripper limitations	3
Motor limitations	3
Multiple arms	3
Payload weight limitations of electric robots	3
Robot size	3

Finally, in terms of longer-term constraints in robotic technology (Table II-35), the major concerns appear to be the continued advancement in machine vision, more sophisticated software to control robots, and enhanced compatability with existing equipment.

TABLE II-35

(G-14a) Degree of Severity of Current Technological Constraints to the More Rapid Utilization of Robots

Technological Barrier	Degree of Importance
Vision systems	2
Software	2
Communication/compatability with existing equipment	2
Non-vision sensors	3
Computer limitations	3
Tooling limitations	3
Repeatability/accuracy	3
Speed	3
Arm oscillations	3
Mobility	3
Parts presentation requirements	3
Accident avoidance	3

*1 = critical; 5 = not important.

SECTION III

TECHNOLOGY

Basic Design

Although there exists a small number of custom-designed robots, the overwhelming majority fall into one of four major categories: articulated (or jointed), cartesian (or rectilinear-coordinate), cylindrical, and spherical (definitions can be found in Appendix A). Half of all robots sold in the U.S. in 1985 are forecast to be of the articulated design (Table III-1). Another 21% will utilize a cartesian coordinate system, 16% a cylindrical design, and the remaining 10% a spherical system. Somewhat surprisingly, there is no change whatsoever in these ratios forecast throughout the next ten years.

TABLE III-1

(T-15) Percentage Distribution of Coordinate Systems

	1985	1990	1995
Articulated	53%	53%	53%
Cartesian	21	21	21
Cylindrical	16	16	16
Spherical	10	10	10
	100%	100%	100%

On the other hand, there will be a noticeable trend away from the mounting of robots in the "traditional" location, on the work floor. New applications and the design of more efficient uses of space will lead to robots mounted on other equipment, suspended from ceilings and walls, and, for smaller units, located on table tops. In 1985, nearly two-thirds of robots purchased will be sited on the floor, with another 20% on tables and the remaining 15% at other locations (Table III-2). However, by 1995, the share of floor-mounted units will drop to only 55%, with most of the difference picked up by ceiling- and wall-mounted robots (5% in 1985 to 11% in 1995). What proved unexpected, however, was the relative constancy in the share of table-top units (22% by 1995), despite the anticipated increase in small-parts assembly and inspection, particularly in the electronics industry.

TABLE III-2
(T-4) Location of Robot Mountings

	1985	1990	1995
Table-top	20%	22%	22%
Floor	65	57	55
Ceiling/wall	5	10	11
Equipment	10	11	12
	100%	100%	100%

Because different robot applications require various degrees of flexibility, units are designed utilizing a number of axes of motion. Overall, it is expected that robot sales will be roughly equally divided among four-, five-, and six-axis units, with only 2-3% equipped with seven different axes (Table III-3), throughout the forecast period. Individual robot applications vary widely as to requirements for degrees of freedom (Tables III-4 through III-12). In the case of the simplest units, those devoted to material transfer, only a minimum number of axes is required for most tasks; thus, two-thirds of these robots will have only four axes (67% in 1985, and 60% in 1995). Similarly, machine-tending robots will also be predominantly four-axis units (53% in 1985; 50% in 1995). At the high end of the scale will be robots assigned tasks where precision is crucial and/or flexibility is required in order to reach obscure areas. A case where both requirements come together is spray coating. For this application, nearly 60% of all units sold will come equipped with six axes of motion (56% in 1985; 59% in 1995), while a significant number will even be designed with seven (5% in 1985; 11% in 1995). Other applications also calling for greater numbers of degrees of freedom include welding (both spot and arc) and assembly.

TABLE III-3

(T-11a) Percentage Distribution of Number of Axes Among All Robots Sold in the Following Years

No. of Axes	1985	1990	1995
4 or fewer	36%	33%	33%
5	30	30	29
6	32	34	35
7	2	3	3
8 or more	0	0	0
	100%	100%	100%

TABLE III-4

(T-11a) Percentage Distribution of Number of Axes in Machine-Tending Robots

No. of Axes	1985	1990	1995
4 or fewer	53%	50%	50%
5	32	30	30
6	15	20	20
7	0	0	0
8 or more	0	0	0
	100%	100%	100%

TABLE III-5

(T-11b) Percentage Distribution of Number of Axes in Material Transfer Robots

No. of Axes	1985	1990	1995
4 or fewer	67%	59%	60%
5	22	29	28
6	11	12	12
7	0	0	0
8 or more	0	0	0
	100%	100%	100%

TABLE III-6

(T-11c) Percentage Distribution of Number of Axes in Spot Welding Robots

No. of Axes	1985	1990	1995
4 or fewer	22%	21%	14%
5	30	29	29
6	45	43	50
7	3	7	7
8 or more	0	0	0
	100%	100%	100%

TABLE III-7

(T-11d) Percentage Distribution of Number of Axes in Arc Welding Robots

No. of Axes	1985	1990	1995
4 or fewer	8%	6%	7%
5	39	32	29
6	47	56	57
7	6	6	7
8 or more	0	0	0
	100%	100%	100%

TABLE III-8

(T-11e) Percentage Distribution of Number of Axes in Spray Painting Robots

No. of Axes	1985	1990	1995
4 or fewer	11%	9%	6%
5	28	28	24
6	56	57	59
7	5	6	11
8 or more	0	0	0
	100%	100%	100%

TABLE III-9

(T-11f) Percentage Distribution of Number of Axes in Processing (e.g., routing, drilling, grinding, etc.) Robots.

No. of Axes	1985	1990	1995
4 or fewer	21%	24%	25%
5	42	35	31
6	32	35	38
7	5	6	6
8 or more	0	0	0
	100%	100%	100%

TABLE III-10

(T-11g) Percentage Distribution of Number of Axes in Electronics Assembly Robots

No. of Axes	1985	1990	1995
4 or fewer	63%	50%	50%
5	25	25	25
6	12	25	25
7	0	0	0
8 or more	0	0	0
	100%	100%	100%

TABLE III-11

(T-11h) Percentage Distribution of Number of Axes in Other Assembly Robots

No. of Axes	1985	1990	1995
4 or fewer	35%	32%	24%
5	35	32	29
6	30	36	47
7	0	0	0
8 or more	0	0	0
	100%	100%	100%

TABLE III-12

(T-11i) Percentage Distribution of Number of Axes in Inspection Robots

No. of Axes	1985	1990	1995
4 or fewer	37%	24%	22%
5	25	29	28
6	38	41	44
7	0	6	6
8 or more	0	0	0
	100%	100%	100%

In no instance was any robot application seen as requiring more than seven axes of motion. Even then, only a small number required seven; these applications were limited to spot and arc welding, spray painting, processing, and inspection. By 1995, still no more than 7% of any of these types of robots will utilize seven axes, with the lone exception of spray painting units (11% by 1995).

Other design aspects that were put to the Delphi panel for consideration included robots equipped with multiple coordinated arms (Table III-13), and those possessing the capacity for mobility (Table III-14). Frequently, these have been considered somewhat futuristic characteristics. However, several research institutions and corporations are devoting a considerable amount of effort in these areas, and the forecast data suggest that these features will begin to see application within the next ten years. By 1995, it is predicted that 15% of robots will have two or more arms, and another 29% will possess some degree of mobility.

TABLE III-13

(T-18) Robots with Two (or more) Coordinated Arms

	1985	1990	1995
All industry	3%	10%	15%

TABLE III-14

(T-35) Robots Possessing Some Degree of Self-propulsion

	1985	1990	1995
Movement along a track	5%	15%	21%
Unlimited mobility	0	5	8
No mobility	95	80	71
	100%	100%	100%

Robot Capabilities

Four major criteria were considered regarding robot performance: velocity, accuracy, repeatability, and load capacity. In 1985, most robots sold will operate at an average velocity of 30-40 inches per second (Table III-15); by 1995, this range is expected to increase to 35-75 inches per second. As might be expected, arc welding robots, with seam-tracking and possibly weld-quality inspection functions being handled at the same time as the actual welding, will remain the slowest of robot applications, while material handling and assembly robots will be the fastest.

TABLE III-15

(T-20a) Average Velocities (inches per second), by Robot Type

	1985	1990	1995
Machine tending	40	40	50
Material transfer (excl. machine tending)	40	60	75
Spot welding	30	40	40
Arc welding	30	35	35
Spray painting/coating	40	50	50
Processing	30	30	40
Electronics assembly	40	50	55
Other assembly	35	50	60
Inspection	40	40	40

Accuracy and repeatability are measurements reflecting different aspects of the same phenomenon: the precision with which a robot operates. In virtually all cases, there is an extremely high correlation between the forecast numbers for accuracy (Table III-16) and those for repeatability (Table III-17).

Rather than a dramatic, explosive improvement in the precision demonstrated by robots, advancement will tend to come gradually. Most of this advancement will stem from improved motor technology, as well as from such items as "jammy" fluids to help dampen arm oscillations. Between 1985 and 1995, the error margin in precision will be reduced to anywhere from one-half (machine tending, material transfer) to one-fifth (spot welding, spray coating) of the earlier values. Among the most precise units are expected to be inspection and electronics assembly robots; the least precise will be those used for spray coating.

TABLE III-16

(T-20b) Average Accuracies (+ - inches per second), by Robot Type

	1985	1990	1995
Machine tending	.01	.005	.005
Material transfer (excl. machine tending)	.02	.01	.005
Spot welding	.01	.01	.01
Arc welding	.01	.007	.004
Spray painting/coating	.05	.05	.05
Processing	.01	.005	.003
Electronics assembly	.005	.002	.001
Other assembly	.005	.004	.003
Inspection	.003	.001	.0005

TABLE III-17

(T-20c) Average Repeatabilities (+ - inches per second), by Robot Type

	1985	1990	1995
Machine tending	.01	.005	.005
Material transfer (excl. machine tending)	.01	.005	.005
Spot welding	.01	.004	.002
Arc welding	.005	.004	.002
Spray painting/coating	.05	.01	.01
Processing	.005	.004	.002
Electronics assembly	.002	.001	.0005
Other assembly	.003	.002	.001
Inspection	.002	.001	.0005

Panelists were also asked to predict the load capacities of robots for several specific applications (Tables III-18 through III-21). For material handling units (a category combining machine tending and material transfer), three-quarters will have capacities of 40 pounds (18.1 kg) or less; half will be 20 pounds (9.1 kg) or less. In the case of processing (e.g., routing, grinding, drilling, etc.) robots, one-third will handle payloads (generally end-effectors) weighing 10 pounds (4.5 kg) or less, while two-thirds will handle 20 pounds and under. Very few will have to contend with weights over 40 pounds (18.1 kg). Electronics assembly units generally will deal with quite small components, and thus they themselves will be small, precise robots with reduced payload capacities. Two-thirds of these units will have maximum payloads of 1 pound (.45 kg) or less; most will be under 1/2 pound (.23 kg). These figures are in contrast with those for other assembly robots, where only one-third are expected to have maximum capacities of 5 pounds (2.3 kg) or under.

TABLE III-18

(G-16a) Percentage Distribution of all Material Handling (i.e., Machine Tending and Material Transfer) Robots Falling Into the Following Load Capacities

	1985	1990	1995
0 - 5 lbs.	16%	19%	22%
5.1 - 10 lbs.	11	12	11
10.1 - 20 lbs.	17	19	17
20.1 - 40 lbs.	34	24	22
40.1 - 60 lbs.	11	14	11
Over 60 lbs.	11	12	17
	100%	100%	100%

TABLE III-19

(G-16b) Percentage Distribution of All Finishing and Processing Robots Falling Into the Following Load Capacities

	1985	1990	1995
0 - 5 lbs.	17%	12%	8%
5.1 - 10 lbs.	17	25	25
10.1 - 20 lbs.	34	31	31
20.1 - 40 lbs.	20	20	20
40.1 - 60 lbs.	6	6	8
Over 60 lbs.	6	6	8
	100%	100%	100%

TABLE III-20

(G-16c) Percentage Distribution of All Electronics Assembly Robots Falling Into the Following Load Capacities

	1985	1990	1995
0 - 0.5 lbs.	45%	47%	40%
0.51 - 1.0 lbs.	23	21	24
1.1 - 3.0 lbs.	17	18	20
3.1 - 5.0 lbs.	9	9	11
Over 5.1 lbs.	6	5	5
	100%	100%	100%

TABLE III-21

(G-16d) Percentage Distribution of All Other Assembly Robots Falling Into the Following Load Capacities

	1985	1990	1995
0 - 5 lbs.	53%	42%	42%
10.1 - 20 lbs.	23	29	29
20.1 - 40 lbs.	12	14	17
40.1 - 60 lbs.	6	8	6
Over 60 lbs.	6	7	6
	100%	100%	100%

TABLE III-22

(T-6) Percentage Distribution of Controller Types

	1985	1990	1995
Microcomputer	48%	53%	56%
Minicomputer	24	29	28
Mainframe computer	4	6	6
Programmable controller	24	12	10
	100%	100%	100%

Control Systems/Programming/Teaching

When asked to predict the types of controllers used in conjunction with robots, the Delphi panel foresaw two interesting trends developing (Table III-22). The first has been widely anticipated: over the next ten years, there will be a marked movement away from the use of programmable controllers in favor of small computers. As robots become more sophisticated, and as they are tied into more systems as opposed to operating as stand-alone units, more computing power will be needed to control their actions precisely. Thus, while nearly a quarter of robots sold in 1985 will operate under a programmable controller, this percentage will drop sharply to 12% by 1990, and to only 10% by 1995.

The second trend is a bit more subtle. Between 1985 and 1995, there will be only a slight growth in the percentage of robots sold to be tied into a mainframe computer (4% in 1985 versus 6% by 1995). Initially, this appears surprising, given the forecast of the up-swing in robots being tied into factory-wide CAD/CAM or CIM systems, and the enormous demands thus placed on the controllers. But there may be a relatively simple explanation contained in panelists' suggestions. Briefly stated, because these large manufacturing systems will operate multiples, and sometimes large multiples, of robots simultaneously, fewer of these mainframe computers will account for the control of an ever larger number of manipulators. Thus, while the number of robots tied into a mainframe will be increasing, the actual number of mainframes used as a percentage of all controllers will tend to remain constant.

Consistent with this trend away from programmable controllers in favor of computers is the method by which robots will be taught their tasks (Table III-23). Presently, the vast majority (83% in 1985) of robots are led through their assigned motions by a technician. Certain key points along the path to be followed by the robot are recorded, with intermediate points interpolated by the controller, usually using a shortest-route algorithm. However, through the application of more sophisticated controllers and software, more complex tasks can be assigned. In addition, the computers can be programmed directly off-line, rather than the robot being physically led. By 1995, half of all the robots controlled by a computer will, in fact, be programmed off-line (Table III-24). Reflecting these advantages is the fact that the share of robots sold requiring point-to-point teaching will decline to only 44% in 1995, with most of these being dedicated to such simple tasks as material transfer.

Another advantage associated with the use of computerized robot control is the use of CAD simulation to design the manufacturing process and subsequently debug the robot programming. While the use of CAD for debugging is still rather limited (5% of robots programmed off-line in 1985), this method will steadily increase in importance; by 1995, some 40% of off-line instructed robots will be so debugged (Table III-25).

TABLE III-23

(T-5) Percentage Distribution of Robot Teach/Programming Modes

	1985	1990	1995
Point-to-point	33%	22%	19%
Control pendant	50	44	25
Computer programming	11	22	31
Other	0	0	0
Hybrid of the above	6	11	25
	100%	100%*	100%

*May not total 100% due to rounding.

TABLE III-24

(T-7) Percent of Computer-Controlled Robots Programmed Off-Line vs. On-Line

	1985	1990	1995
Off-line	15%	35%	50%
On-line	85	65	50
	100%	100%	100%

TABLE III-25

(T-8) Percent of Robots Programmed Off-Line That Will be Debugged Using a CAD Simulator

	1985	1990	1995
Robots debugged via CAD	5%	20%	40%

An outgrowth of the use of computers for programming robots will be the creation of commercial time-sharing services with standard software packages specifically for this purpose. While use of this service will probably remain limited (Table III-26), it still may represent a significant area of growth for time-sharing services.

TABLE III-26

(G-20a) Percent of All Robots Utilizing Commercial Time-Sharing Services for Robot Programming

	1985	1990	1995
Percent of all robots	5%	10%	15%

Much of this advance in robot control is based upon the assumption that there will be some degree of standardization in programming languages to facilitate communications between various types of automation equipment. Unfortunately, when asked about the probability of such a language or set of languages being developed in the near future, the panel was quite pessimistic, rating the odds as only 1 in 4 that this might happen by 1995 (Table III-27).

TABLE III-27

(T-36 & T-37) Probability of Having Standardized Off-Line and On-Line Robot Programming Languages

	1985	1990	1995
Odds of standardized off-line	0%	10%	25%
Odds of standardized on-line	0	10	20

Actuators

Although early robots utilized hydraulic actuators, and soon thereafter pneumatic actuators, the majority of new robots sold today are operated by electric motors. This trend toward electrically powered robots is expected by most sources to continue, if not increase, over time as better motors are developed.

Thus, the Delphi panelists were asked about the advantages associated with these various types of actuators (Table III-28). Electrically driven robots were cited as possessing enhanced precision characteristics: better accuracy, repeatability, and spatial resolution. In addition, the reduced mean time before failure was listed as another major asset. Benefits derived from the use of hydraulic activators included increased payload capacity, better speed of operation, and good repeatability and accuracy. These features will assure that hydraulic robots will find continued use in industry. The main advantage of pneumatic units stems from cost. Because of the simplicity of design, these robots were judged as having both a lower initial cost and a lower cost of upkeep. Other advantages include suitability for use in flammable environments and speed.

TABLE III-28

(T-16) Ranking of Advantages Associated with Various Actuator Types

	Hydraulic	Electric	Pneumatic
Initial cost	5	8	1
Maintenance cost	6	6	3
Load capability	1	10	6
Energy usage	12	11	11
Floor space	13	12	8
Use in flammable environment	11	13	2
Spatial resolution	9	3	13
Accuracy	4	1	9
Compliance	7	9	12
Repeatability	3	2	10
Speed	2	5	4
Mean time before failure	8	4	5
Ease of introduction	10	7	7

Sensor Technology

Presently, comparatively few robots are being sold with any type of sensor (Table III-29). In 1985, only 15% of all robots sold will be sensor-equipped. However, as more sophisticated applications of robots are found in which feedback is critical, and as the emphasis on sensor research and development, particularly in machine vision, is continued, most robots sold in 1995 will contain one or more sensors.

TABLE III-29
(T-2) Percent of All Industrial Robots Including Any Sort of Feedback-Sensing Device

	1985	1990	1995
Percent of all robots	15%	35%	60%

The use of machine vision is expected to find its way into all applications of robots (Table III-30). The panel estimated that, currently, about 5% of robots sold in the U.S. are equipped with some form of vision, a figure many felt was quite optimistic. Inspection units are predicted to account for one-fifth of these sales, with assembly robots for another one-fifth. By 1995, machine vision will represent the most widely applied form of sensor, with nearly 27% of all robots sold being so equipped. Of these, inspection units will again claim one-fifth of total sales, while assembly robots will account for nearly two-fifths.

TABLE III-30

(T-21) Percent of New Robots Including a Machine Vision Capability

	1985	1990	1995
Machine tending	5%	10%	15%
Material transfer (excl. machine tending)	5	10	15
Spot welding	3	5	10
Arc welding	5	20	30
Spray painting/coating	2	5	10
Electronics assembly	10	30	45
Other assembly	10	20	35
Inspection	20	40	60

Among robots equipped with machine vision, only a relatively small percentage will be sophisticated enough to handle the so-called "bin-picking" problem; i.e., to identify an object jumbled among other objects, and guide a robot to pick up the part in an acceptable orientation (Table III-31). Even by 1995, only 18% of robots furnished with vision will be able to handle this sort of problem.

TABLE III-31

(T-24) Percent of All Vision-Equipped Robots Capable of "Scene Analysis" for Bin-Picking Applications

	1985	1990	1995
Percent of all robots	2%	10%	18%

Another advanced feature of vision-equipped arc welding robots will be a seam-tracking ability. At present, the technology for this application is still being refined; however, by 1995, the percentage of seam-tracking, arc-welding robots is expected to be as high as 55%.

TABLE III-32

(T-25) Percent of All Arc Welding Robots Incorporating A Seam-Tracking Mechanism

	1985	1990	1995
Percent of arc welding robots	15%	35%	55%

TABLE III-33

(T-27) Percent of New Robots Including a Touch or Force Sensing Device with Feedback

	1985	1990	1995
Machine tending	5%	15%	25%
Material transfer (excl. machine tending)	5	15	30
Spot welding	5	5	10
Arc welding	5	10	10
Spray painting/coating	0	0	0
Processing	5	20	40
Electronics assembly	10	20	40
Other assembly	10	25	40
Inspection	5	15	20

Tactile, or contact, systems are also anticipated to play a major role in robotic sensing. Once again, the panel estimated that about 5% of robots sold in 1985 will utilize some form of this type of sensor, another quite optimistic assessment, according to some. Significant applications will include material handling robots (both machine loading and material transfer), representing one-third of units sold with tactile sensors, and assembly robots (22% of tactile sales). The percentage of robots with tactile equipment in 1995 is forecast to rise to over 25% of all sales. Major applications will again be for assembly (41% of all tactile-equipped robots sold) and material handling (32%).

Lastly, panelists were asked to consider the use of non-vision, non-tactile sensors such as proximity and range detectors, and temperature sensors (Table III-34). In 1985, it is expected that 6% of all robots sold will possess this type of sensor, making it the most widely utilized sensor type in the near term. While applications seem to be fairly evenly distributed, the one exception is in material handling, where two-fifths of these sensors installed into robots will be located. By 1995, 26% of robots sold will contain one or more of these sensors, with assembly units leading the way (33% of sales of non-vision, non-tactile sensor-equipped robots), followed by material handling (29%), and inspection (15%).

Among the non-vision, non-tactile sensors, proximity detectors are expected to represent by far the most widely used system (Table III-35). In 1985, proximity units will account for 67% of the applications of this type of sensor, declining slightly to 61% by 1995. The next largest segment will be range detectors, with a constant 28% share. The only other type mentioned were temperature detectors, with a small (5%) share in 1985, rising to 11% by 1995.

From Tables III-29, III-30, III-33, and III-34, the percentage of robots with multiple sensors can be estimated. By summing the data contained in the last three tables, a maximum possible percentage of robots equipped with any type of sensors can be calculated by initially assuming no multiple sensors. Then by subtracting the figures in Table III-29, i.e., the actual percentage of all robots equipped with one or more sensors, from the theoretical maximum yields the percentage of robots with multiple sensors. This has been done in Table III-36.

TABLE III-34

(T-30) Percent of New Robots Including Any Sort of Non-Vision, Non-Contact Sensing Device with Feedback (e.g., Proximity and/or Range Detectors, Temperature Detectors, etc.).

	1985	1990	1995
Machine tending	5%	15%	20%
Material transfer (excl. machine tending)	10	20	30
Spot welding	5	10	10
Arc welding	5	15	30
Spray painting/coating	3	5	10
Processing	5	15	20
Electronics assembly	5	20	35
Other assembly	10	20	30
Inspection	10	30	40

TABLE III-35

(T-31) Distribution of Types of Non-Vision, Non-Contact Sensors Incorporated Into New Robots

	1985	1990	1995
Proximity detectors	67%	65%	61%
Range detectors	28	29	28
Temperature detectors	5	6	11
Other	0	0	0
	100%	100%	100%

TABLE III-36

Robots Equipped with Multiple Sensors

	1985	1990	1995
(T-21) Robots with vision	5.5%	15.0%	26.6%
(T-27) Robots with tactile sensor	5.1	13.3	25.4
(T-30) Robots with other sensor	6.1	16.0	25.8
Maximum % with some sensor	16.7%	44.3%	77.8%
(T-2) Total robots with sensors	15.0	35.0	60.0
Robots with multiple sensors	1.7	9.3	17.8

Finally, the Delphi panelists were asked to estimate the severity of limitation in the application of robots that sensor technology currently represents. As the comparatively large numbers of robots expected to utilize some form of sensor indicate, these limitations are viewed by the panel quite seriously (Table III-37). While significant strides have been made in non-vision sensors, thus reducing the number of limitations to their use, the potentially most powerful type of sensor, machine vision, is still in its infancy. Thus, it is viewed as a key bottleneck to the wider implementation of robots in U.S. industry.

TABLE III-37

(G-14a) Ranking of Importance of Current Barriers in Sensor Technology to the More Rapid Utilization of Robots by U.S. Manufacturers (1=critical; 5=not important)

	Degree of Severity
Vision systems	2
Non-vision sensors	3

SECTION IV

SOCIOLOGY

Over the past few years, one of the most frequently discussed workplace issues today has centered upon the potential social impacts of automation. Opinions covering virtually the entire spectrum can be found all the way from large-scale media reports down to individual conversations between factory workers and managers. On the one hand, many, especially in labor, feel that as robots become increasingly inexpensive, adaptable, and commonplace, many jobs will be irretrievably lost, and remaining workers will suffer real losses in income as they attempt to hold on to what jobs are left. Alternatively, others, notably in management, believe that only low-skill, dangerous, and monotonous jobs will be taken over by robots, and that with retraining and ongoing educational efforts, virtually all displaced workers will end up with more satisfying and rewarding employment; further, that new employment opportunities will be created out of the benefits of enhanced productivity, and an increase in demand for goods and services will be derived from lower prices. The truth undoubtedly will lie somewhere between these extremes.

Because trends in employment are a central issue in the more widespread application of robots in the workplace, the Delphi panelists were asked to address matters of worker displacement, attitudes, and education and retraining. Among the major conclusions is the forecast that while some industries and specific occupations will suffer as much as 20% displacement of workers, these are definitely the exceptions rather than the norm. And of all workers displaced by robots, over three-quarters will be given new jobs within the same plant; only 5% to 6% of displaced workers will actually be left without a job in the company.

These figures highlight the need to be aware of a critical distinction assumed throughout this section: displacement is not the same as disemployment. Displacement only refers to those jobs which have been taken over by robots; the affected workers are not necessarily let go, or disemployed. And as our panelists suggest, the disparity between these numbers is extremely large.

Potential Employment Consequences of Robots

One of labor's major concerns centers on the installation of robots as a way to reduce the levels of comparatively expensive worker input. While many in management have not denied this as one motivation, they have also pointed to such goals as enhanced product quality, fewer defects, and a better flow of materials as other potentially sizable contributors to savings. Clearly, however, the role of labor replacement in the decision to robotize remains a critical issue.

To address this topic, panelists were asked to forecast the importance of ten sources of savings frequently associated with the use of robots; among these sources were both direct and indirect labor cost savings. Respondents were asked to assign a percentage of total cost savings to each of these factors. The full set of responses can be found in the General Trends section (Tables II-12 through II-22); however, a summary of the percentages assigned to direct and indirect labor cost savings is presented in Tables IV-1 and IV-2.

TABLE IV-1

(S-27) Percent of All Production Savings Represented by Reduction in Direct Labor Costs, by Robot Application

	1985	1990	1995
Machine tending	93%	86%	74%
Material transfer	56	56	55
Spot welding	50	58	60
Arc welding	62	58	54
Spray painting/coating	40	38	34
Processing (routing, drilling grinding, etc.)	50	50	50
Electronics assembly	38	40	41
Other assembly	41	44	47
Inspection	55	51	46

TABLE IV-2

(S-27) Percent of All Production Savings Represented by Indirect Labor Productivity Gains, by Robot Application

	1985	1990	1995
Machine tending	1%	1%	1%
Material transfer	11	12	12
Spot welding	6	6	6
Arc welding	8	6	5
Spray painting/coating	6	6	6
Processing (routing, drilling grinding, etc.)	6	6	7
Electronics assembly	6	5	5
Other assembly	13	13	13
Inspection	9	7	8

As would be expected, the percentages associated with direct labor replacement vary considerably, depending on application. The highest figures tend to be associated with lower-skill occupations, such as machine loading and materials transfer, where functions are very mechanical and relatively limited. Higher-skill tasks, such as electronics assembly and spray painting, require more sophisticated robots, thereby tending to reduce the cost advantage over human laborers. Nevertheless, in most robot applications, reduction in combined direct and indirect labor costs represents over half of the total savings associated with robotics (Table IV-3). These numbers represent significant increases over estimates provided in the earlier 1982 Delphi Robotics study.

TABLE IV-3

(S-27) Percent of All Production Savings Represented by
Total Labor Replacement (Direct Plus Indirect),
by Robot Application

	1985		1990		1995	
	Delphi II	Delphi I	Delphi II	Delphi I	Delphi II	Delphi I
Machine tending	94%	--	87%	--	75%	--
Material transfer	67	67	68	59	67	59
Spot welding	56	--	64	--	66	--
Arc welding	70	66	64	56	61	45
Spray painting/coating	46	54	44	57	40	44
Processing	56	66	56	58	57	48
Electronics ass'y	44	--	45	--	46	--
Inspection	64	n/a	58	n/a	54	n/a

Displacement Levels by Industry

Because of its relatively early and intensive use of such automation, the automotive industry is forecast to retain its distinction as the industry with the highest displacement levels among production workers caused by robots over the course of the next decade, from 5% in 1985 (or approximately 25,000 workers) to 18% (90,000 workers) by 1995 (Table IV-4). However, as investment in precision assembly and inspection units increases, the electronics industry will nearly match these percentages, from 3% of production workers in 1985 to 15% by 1995. Other sectors undergoing significant worker displacement will include primary metals (10% by 1995), consumer non-durables (10%), and aerospace (9%). At the low end of the scale, panelists foresaw little, if any, displacement in such areas as agriculture, construction, and electricity (primarily nuclear) generation. This is most likely due to the expected low penetration rate of robots into the workplace in these industries to begin with (see Table II-2 in the General Trends section).

TABLE IV-4

(S-3) Percentage of U.S. Production Workers Actually Displaced as a Result of the Installation of Robots, by Industry

	1985	1990	1995
Agriculture	0%	0%	1%
Mining and extractive	.5	2	4
Construction	0	0	1
Electricity generation	0	0	1
Consumer non-durables	2	4	10
Non-metal primary commodities	1	4	7
Primary metals	.5	4	10
Non-metal fabricated commodities	1	3	6
Fabricated metal products	2	5	8
Machinery manufacture	1	3	6
Electronics	3	10	15
Automotive	5	10	18
Aerospace	2	5	9
Other transportation equipment	2	3	8

In terms of employment levels, however, the introduction of robotics into these industries will have a less serious impact (Table IV-5). There is a strong correlation between displacement levels and a decrease in production man-hour requirements; but in virtually all cases, these man-hour requirement changes will be less significant than displacement, indicating that many workers will remain employed in new positions.

TABLE IV-5
(S-6) Percent Change in Total Number of Production Man-Hours Required Due to Robots, by Industry.

	1985	1990	1995
Agriculture	0%	0%	0%
Mining and extractive	0	-1.5	-2
Construction	0	0	0
Electricity generation	0	0	0
Consumer non-durables	-1	-3	-5
Non-metal primary commodities	0	0	0
Non-metal fabricated commodities	-1	0	3
Fabricated metal products	-1	-5	-10
Machinery manufacture	-2	-5	-7
Electronics	0	-4	-8
Automotive	-5	-10	-15
Aerospace	0	-1	-6
Other transportation equipment	-1	-3	-7

When considering the net effect on employment, there are other factors which also enter into the picture. These include the declining entry rate into the work force of women and new workers, the aging of the work force as well as greater levels of early retirement, and the possible continued reduction in the hours constituting an average work week. These will be considered in a later section.

Displacement Levels by Occupation

Besides examining displacement effects by industry, the study also looked at various individual occupations most likely to be affected by the introduction of robots (Table IV-6). Among the job classifications most affected will be industrial welders (20% displacement by 1995; or approximately 120,000 jobs), production painters (also 20% displacement by 1995; 28,000 jobs), machinists and machinery operators (13%; 112,000 jobs), and assemblers (10%; 109,000 jobs). Other occupations involving significant numbers of displaced individuals include textile workers (5%; 50,000 jobs), inspectors (6%; 44,000 jobs), and industrial packers (5%; 29,000 jobs). It is also noteworthy that among the twelve occupations listed, the overall displacement rate will only be 4.3% by 1995. Actual disemployment is expected to be far less.

TABLE IV-6

(S-2) Percentage of U.S. Production Workers Actually Displaced as a Result of the Installation of Robots, by Occupation

	1985	1990	1995
Assemblers	2%	5%	10%
Inspectors	1	3	6
Packers (excl. meat & produce)	1	2	5
Production painters	5	10	20
Welders and flamecutters	5	10	20
Machinists & machinery oper's.	3	10	13
Tool and die makers	0	1	2
Metalcraft workers	1	3	6
Construction crafts	0	0	1
Textile workers	1	2	5
Mining workers	0	2	4
Agricultural workers	0	1	2

Also examined were the employment impacts of the use of robots on various non-production workers (Table IV-7). While no change is foreseen in the administrative, secretarial/clerical, and support services ranks, the increased use of robotics will increase employment opportunities among engineering staff, computer programmers, and machine maintenance personnel by 6-7% by 1995. Requirements for line supervisory staff is forecast to decline by 3% during the same period.

TABLE IV-7

(S-4) Percentage of U.S. Non-Production Personnel Actually Displaced as a Result of the Installation of Robots, by Occupation

	1985	1990	1995
Upper administration and managerial	0%	0%	0%
Secretarial & clerical	0	0	0
Engineering and computer programmers	1	3	6
Line supervisory	-1	-2	-3
Machine maintenance	2	3	7
Building maintenance	0	0	0
Medical & other services	0	0	0

Displacement by Robot Application

Lastly on the subject of worker displacement, the Delphi panel was asked to estimate the typical number of workers affected by various types of robots in two-shift operations (Table IV-8). While the near-term values ranged between two and three workers per robot, they are expected to increase to between three and four by 1995. This trend is due both to increased robot sophistication and to greater familiarity on the part of the robot users as to the capabilities and potential applications of the units.

TABLE IV-8

(S-14) Number of Workers Typically Displaced by a Single Robot in a Two-Shift Operation, by Application

	1985	1990	1995
Machine tending	2	3	3
Material transfer	2	3	4
Spot welding	3	4	4
Arc welding	3	3	4
Spray painting/coating	3	3	3
Processing	2	3	3
Electronics assembly	3	4	4
Other assembly	2	3	3
Inspection	2	2	3

Net Effects on Employment

As mentioned earlier, the vast majority of displaced workers are expected to remain within the same company, most within the same facility (Table IV-9). Only 5% of displaced workers in 1985, and 6% in 1995, are forecast to quit or be fired as a result of the introduction of robots into the workplace; an additional 5% will opt for early retirement. Thus, nearly 90% of affected workers will remain with the company.

Of those workers remaining, over one-third will receive some form of retraining during 1985. By 1995, the fraction will be over half (56%). Clearly, there will be a need for retraining as new forms of automation are introduced into the factories. This subject is addressed in a later section.

TABLE IV-9

(S-13a) Disposition of Displaced Workers

	1985	1990	1995
Transferred within plant, no retraining	51%	39%	33%
Transferred within plant, with retraining	31	39	44
Transferred to another plant, no retraining	5	6	6
Transferred to another plant, with retraining	3	6	6
Early retirement	5	5	5
Voluntary termination (quits)	4	4	4
Involuntary termination (fires)	1	1	2
Other	0	0	0
	100%	100%	100%

There is also the question as to what sorts of jobs the displaced but kept workers will end up with. Many have felt that there will be little room for advancement, as the requirements for higher education would block these opportunities from the affected workers. Instead, according to this view, these workers would be assigned to menial jobs for which they were overqualified. However, the forecast data suggest that these fears, while justified, may be exaggerated (Table IV-10). The great majority of resituated workers are expected to receive lateral transfers to new jobs requiring skill levels comparable to the level of their previous positions; an additional 10% will actually receive promotions, most likely after comprehensive retraining. Only 10% will be demoted, a percentage that many firms will try to reduce further.

TABLE IV-10

(S-13b) Disposition of Workers Transferred Due to the Installation of Robots

	1985	1990	1995
Promotions	5%	10%	10%
Demotions	11	10	10
Lateral transfers	84	80	80
	100%	100%	100%

TABLE IV-11

(S-13c) Length of Time for Terminated Workers to Obtain New Employment

	1985	1990	1995
2 months or less	8%	9%	10%
2 to 6 months	25	26	27
6 to 12 months	34	35	36
1 to 2 years	17	18	18
More than 2 years	8	6	2
Will not find new full-time employment	8	6	7
	100%	100%	100%

And what of the terminated workers? While panelists suggested that the search for new full-time employment may not be as easy as it once was, a third or more of these people will find new jobs within six months (33% in 1985, up to 37% in 1995). A sizable majority will still find alternative employment within a year (67% in 1985, versus 73% in 1995). Some 6 to 8 percent may become permanently disemployed, due to a lack of marketable skills; among the twelve job classifications examined in this survey (Table IV-6), which are expected to represent those most highly affected by robots, this amounts to fewer than 1,000 jobs, or 9/1000s of one percent of the nearly 11 million workers in these occupations in 1985. By 1995, although the absolute numbers will be higher, the percentages will remain roughly constant.

Finally, there is the matter of physical relocation by terminated workers finding new jobs (Table IV-12). Roughly two-thirds of these people will find employment close to home, within 25 miles or less. Another one-quarter will be within a two-hour drive, allowing the worker to at least postpone the immediate need to move. Only 12 to 14 percent will have to travel over 100 miles in order to obtain new employment.

TABLE IV-12

(S-13d) Distance That Terminated Workers Will Have to Relocate in Order to Obtain New Employment

	1985	1990	1995
Less than 25 miles	66%	65%	63%
25 to 100 miles	20	22	25
101 to 250 miles	3	5	6
Over 250 miles	11	8	6
	100%	100%	100%

Additional Employment Associated with Robotics

During the 1960s and much of the 1970s, there was widespread concern that the rapidly increasing presence of the computer in the office would lead to the massive disemployment of staff across the board, regardless of position. The image of an employee coming in one morning to find a computer installed at his or her station was not uncommon during that time. However, today these fears have proven for the most part groundless. In fact, a strong argument can be, and has been, made that the computer revolution has created more jobs than it has eliminated; it is the nature of these new jobs that has changed, along with the skills necessary to occupy them.

In the 1980s, a similar wave of concern regarding the disemployment effects associated with the utilization of robotic equipment has been under way. Although the focus has been on production-level jobs rather than on office positions, there have been widespread fears again that workers will report for duty one day only to find that a robot has suddenly rendered them obsolete. For this reason, some industrial unions have mounted active and vitriolic campaigns against the introduction of automation into the workplace. Others have yielded to the competitive pressures of industry and negotiated settlements in an attempt to maximize the number of remaining jobs.

However, as with the computer revolution, the robot revolution also appears to hold the promise of creating jobs as well as competing for them. The most obvious source of new employment is within the manufacture of the robots themselves. According to the forecast results, an estimated 500 man-hours on the average will be required for the production of each robot in 1985; by 1995, this requirement will be reduced to 390 (Table IV-13). By combining this information with anticipated robot production levels in these years (General Trends section, Table II-1), this translates into approximately 1,300 production jobs in 1985, and over 3,000 jobs by 1995.

TABLE IV-13

(S-15a) Average Labor Input, in Man-Hours, Required for the Manufacture of One Robot

	1985	1990	1995
Man-hours per robot	500	400	390

In addition, there will be a significant number of positions created within those industries supplying the robot manufacturers (Table IV-14). It is predicted that for every ten robots produced, there will be two production jobs created among supplier companies in 1985; this number will increase to three by 1995, presumably as robots become more complex. Again comparing these figures against production, some 1,000 additional jobs will appear in these industries by 1985; about 4,500 additional jobs will be available by 1995.

TABLE IV-14

(S-15b) Total Jobs Created in Supplier Industries to Robot Producers for Every 10 Robots Made

	1985	1990	1995
Supplier industry jobs/10 robots	2	2	3

Whereas these positions in the robot manufacturing and supplier industries rely upon the level of annual production of units, job creation among the end-users is related to the cumulative robot population. Thus, the real potential for hiring into robot-related positions lies in this sector. These new jobs involve the maintenance and programming of robots, which will be ongoing requirements. Recently, General Motors Corporation estimated that their requirements for robot maintenance workers was approximately three for every ten robots in operation. The Delphi panelists agreed that this was a reasonable figure for most applications by 1985 (Table IV-15), but when workers have attained the necessary expertise, only two such workers would be needed by 1995. A similar phenomenon is foreseen in the requirement for robot programmers, with two needed for every ten robots currently, and only one by 1995. When translated into total jobs in 1985, the numbers come to nearly 5,500 maintenance workers and 3,700 programmers. By 1995, the respective employment figures will be approximately 25,300 maintenance and 12,600 programming jobs (Table IV-16).

TABLE IV-15

(S-24) Full-time Workers Required per 10 Robots in Operation

	1985	1990	1995
Maintenance workers	3	3	2
Programmers	2	1	1
Total	5	4	3

Thus, the panel expects a sizable level of employment resulting directly from the increased use of robots. This level is calculated at over 11,000 jobs in 1985, and over 45,000 by 1995. These statistics also do not reflect increases throughout the economy indirectly resulting from the increased production efficiencies, lower consumer prices, and concomitant higher disposable incomes. This ripple, or multiplier, effect has so far proven elusive to measure precisely, but may reasonably be expected to be significant, and lead to even more jobs available, not only in manufacturing, but particularly in the services sector.

Education and Training Issues

Again as with the growth in the use of computers in the workplace, perhaps the single greatest area of change that will be wrought by robotization will be the need for a better-educated labor force. The relatively standardized, routine occupations requiring little formal training or skills are exactly the jobs that will find the most robots filling them. Workers

TABLE IV-16

Calculations for New Employment Created by the Use of Robots

	1985	1990	1995
Employment in Robot Industry			
(S-15a) Man-hours per robot	500	400	390
(T-1) Annual robot sales	× 5,000	11,000	15,000
Average annual man-hours per job*	÷ 1,920	1,920	1,920
Employment in robot industry	1,302	2,292	3,047
Employment in Supplier Industries			
(S-15b) Jobs in supplier industries per 10 robots produced	2	2	3
(T-1) Annual robot sales	5,000	11,000	15,000
Employment in supplier industries	1,000	2,200	4,500
Employment Among Users			
(S-24a) Maintenance workers required per 10 operating robots	3	3	2
(T-1) Total robot population	18,300	60,000	126,500
Maintenance employment	5,490	18,000	25,300
(S-24b) Programmers required per 10 operating robots	2	1	1
(T-1) Total robot population	18,300	60,000	126,500
Programmer employment	3,660	6,000	12,650
Total Employment Associated With the Use of Robots	11,452	28,492	45,497

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*Based on 40 hours per week, 48 weeks per year.

previously performing these tasks will be left with two basic options: either to take even more mindless (and lower-paying) jobs that are not economically feasible to automate, or to move up to higher-skill positions. Thus, as has been true in every technological revolution, the need for more education for workers is paramount.

As a result, it is predicted that over the next ten years, the percentage of high school dropouts among the total work force will drop sharply by 1995 compared to the 1980 level, from 22.6% to a still-high 13% (Table IV-17). An equivalent percentage (11%) will go on to receive at least some post-secondary education.

TABLE IV-17

(S-23a) Distribution of Highest Educational Attainment Among the Work Force

	Actual 1980	1985	1990	1995
No H.S. diploma	22.6%	20%	16%	13%
H.S. diploma	40.2	40	40	39
Some college	18.1	20	21	24
Bachelor's degree	11.0	12	14	14
Advanced study	8.1	8	9	10
	100.0%	100%	100%	100%

With specific regard to workers in robotics-related positions, panelists were asked about the importance of the previous acquisition of various skills (Table IV-18). All of the skills listed are seen as having at least some degree of importance, and not changing very much in importance over time. Of critical importance was a thorough familiarity with the principles of electronics. Various other general skills (mechanical, electrical, preventive maintenance) were also ranked very important. The one attribute seen as rising in importance is computer programming. As most robots today remain as stand-alone units, frequently "taught" by physically leading them through the motions, programming is presently a low priority. However, as more robots are tied into centralized CAD/CAM or CIM operations, programming skills will become an increasingly decisive factor in the hiring of workers.

TABLE IV-18

(S-22) Degree of Importance of the Previous Acquisition of Various Skills Toward the Successful Training of a Robotics Maintenance Worker
(1 = critical; 5 = not important)

	1985	1990
Electronics skills	1	1
General electrical skills	2	2
General mechanical skills	2	2
General "preventive" maintenance	2	2
Knowledge of numerical controls	2	2
Programming skills	3	2
Knowledge of hydraulic valves	3	3

Where will these better-trained workers come from? There are currently three main sources: young men and women newly entering the labor force, present workers already possessing the requisite skills, and retrained workers. In 1985, nearly three of every five persons handling robots will be a retrained worker (Table IV-19); only one-quarter of these will be graduates of a robotics program; the remaining 17% will come from other sources. Over time, however, the role of retrained workers will diminish, as present workers approach retirement and more institutions establish robotics curricula. By 1995, only one-third of robotics personnel will be retrained workers, while half will be graduates of institutional programs.

TABLE IV-19

(S-8) Percentage Breakdown of Sources of Robotics Technical Personnel

	1985	1990	1995
Graduates of specialized technical school or junior college programs	12%	17%	28%
Graduating college students	12	22	22
Retrained in-house personnel	59	44	33
Experienced personnel from other manufacturers	12	11	11
Experienced personnel from robot vendors	5	6	6
Other	0	0	0
	100%	100%	100%

Many junior and community colleges, along with other institutions, have already established a robotics-based curriculum. In fact, the concern has been widely expressed that there might already be too many such programs, that graduates may have difficulty in finding suitable employment. The Delphi panel, composed of both industrialists and educators, think not (Table IV-20). When asked to estimate the percentage of such graduates that will find meaningful jobs, the strong response was 100% through 1995, a very optimistic assessment.

TABLE IV-20

(S-12b) Percent of Newly Trained Potential Robotics Workers Finding Employment

	1985	1990	1995
Installers, maintenance, etc.	100%	100%	100%
Programmers and operators	100%	100%	100%

Where will the funds for these programs come from? The major source will be donations from private industry (Tables IV-21 and IV-22), in the form of grants to institutions and individual scholarships. Many corporations view such funding as an investment in a future source of much-needed skilled labor. Government at all levels is expected to provide from 12% to 17% of the funds, and the trainees themselves will be expected to chip in from 6% to 15% of the costs.

TABLE IV-21

(S-9a) Sources of Funding for Training New Robotics Installation, Maintenance, and Oversight Personnel

	1985	1990	1995
Federal government	6%	6%	8%
State and local governments	6	9	9
Private industry	76	66	60
Unions	0	0	0
Universities and institutions	6	6	8
Trainees themselves	6	13	15
Other	0	0	0
	100%	100%	100%

TABLE IV-22

(S-9b) Sources of Funding for Training New Robotics Personnel for Programming and Operational Duties

	1985	1990	1995
Federal government	6%	6%	6%
State and local governments	6	6	6
Private industry	70	70	71
Unions	0	0	0
Universities and institutions	6	6	6
Trainees themselves	12	12	11
Other	0	0	0
	100%	100%	100%

The percentages are quite similar for the funds used to retrain workers. Again, private industry is expected to foot approximately two-thirds of the bill; however, the trainees are expected to provide only 6% to 7% of the funds; government sources will pick up another quarter (Table IV-23).

TABLE IV-23

(S-10) Sources of Funding for Retraining Displaced Personnel to Handle Installation, Maintenance, and Oversight Functions

	1985	1990	1995
Federal government	11%	11%	12%
State and local governments	11	11	12
Private industry	68	68	68
Unions	4	3	1
Universities and institutions	0	0	0
Trainees themselves	6	7	7
Other	0	0	0
	100%	100%	100%

Because, in many cases, retraining is viewed as a stop-gap measure until more thoroughly trained professionals become available, the periods of time required for such programs are fairly short (Table IV-24). Most maintenance workers are expected to be taught the necessary skills in about six work weeks, while equipment operators and programmers (assuming they already have requisite programming skills) will be retrained in two weeks. Supervisors and schedulers will only require one week.

TABLE IV-24

(S-11) Average Retraining Period (in days) Required for the Acquisition of Various Robot-Related Skills

	1985	1990	1995
Maintenance	30	30	25
Production scheduling	5	10	7
Equipment operation	10	10	10
Programming	10	15	10
Line supervisory	5	7	5

The Role of the Unions

The responses of various U.S. labor unions have been extremely varied. Some have reacted stongly against the introduction of robots into the workplace, fearing an inevitable decline in employment, and consequently membership. Others, fearing that lower-cost imports might lead to the loss of even more jobs, have agreed to cooperate as fully as possible in hopes of easing the impacts on their memberships.

Of interest were the incentives management could offer organized labor to help gain cooperation, and the likelihood of management actually offering these incentives (Tables IV-25 and IV-26). As might well be expected, the most powerful potential inducement was a guarantee of continued employment for all workers; unfortunately, as the panel agreed, this is in many cases economically unfeasible. Other influential incentives include retraining provisions, the sharing of productivity benefits in the form of higher wages and fringes, a reduced work week at no loss of pay, and advance notice of technological changes in production.

TABLE IV-25

(S-20a) Rank Ordering of the Potential Effectiveness of Various Incentives to Gain Union Acceptance for the Installation of Robots

	1985	1990	1995
Guaranteed continued employment	1	1	1
Retraining provisions	2	2	2
Sharing of productivity benefits	3	3	3
Reduced work week at no loss of income	4	4	4
Advance notice of technological changes	5	5	5
Supplemental unemployment benefits	6	6	6
Increased paid personal holidays	7	7	7
Increased severance pay	8	8	8
Payment of union dues by robots	9	9	9

III-26

(S-20a) Rank Ordering of the Likelihood of Implementation of Various Incentives to Gain Union Acceptance for the Installation of Robots

	1985	1990	1995
Retraining provisions	1	1	1
Advance notice of technological changes	2	2	2
Supplemental unemployment benefits	3	4	4
Sharing of productivity benefits	4	3	3
Increased severence pay	5	5	5
Guaranteed continued employment	6	6	6
Increased paid personal holidays	7	8	8
Reduced work week at no loss of income	8	7	7
Payment of union dues by robots	9	9	9

The forecasters also predicted that management would agree to the retraining provisions and advance notice provisions, along with supplemental unemployment benefits, increased severance pay, and some sharing of productivity benefits. Thus, the emphasis of the unions will likely remain on continued employment, while management will maintain its offers of liberalized benefits for displaced and disemployed workers. But the panel still sees definite signs of a workable middle ground.

APPENDICES

APPENDIX A

DELPHI FORECAST RESULTS

SME/UNIVERSITY OF MICHIGAN
1984 ROBOTICS DELPHI QUESTIONNAIRE

General Trends

G-1. In 1984, a total of approximately 4200 industrial robots were purchased in the U.S. How many units do you estimate will be purchased by U.S. industry during each of the following years?

All Industry	Median
1985	5000
1986	6000
1987	7000
1988	8200
1989	9500
1990	11,000
1995	15,000
2000	20,000

All Industry	Interquartile Range
1985	4600/5500
1986	5200/7000
1987	6000/8200
1988	7000/10,000
1989	7500/12,000
1990	9000/15,000
1995	12,000/20,000
2000	14,000/35,000

Comments:

1989 - 2000 dependent on technical advances. Too early to predict.

1986 is anticipated to be a recession year. By 1989 assembly should start its impact on robot technology.

G-2. Given the industrial robot sales projected in question G-1, how will these sales be distributed by robot type? (Note that vertical columns must necessarily total 100%).

	Median Percent of Total Sales		
	1985	1990	1995
Machine tending	16%	15%	15%
Material transfer (excl. machine tending)	16%	15%	15%
Spot welding	26%	15%	10%
Arc welding	10%	10%	9%
Spray painting/coating	10%	10%	7%
Processing (routing, drilling, grinding, etc.)	5%	7%	7%
Electronics assembly	6%	12%	14%
Other assembly	5%	8%	12%
Inspection	5%	7%	10%
Other	1%	1%	1%
	100%	100%	100%

	Interquartile Range Percent of Total Sales		
	1985	1990	1995
Machine tending	10/20%	10/20%	10/15%
Material transfer (excl. machine tending)	10/20%	10/20%	10/16%
Spot welding	15/30%	10/20%	8/14%
Arc welding	5/10%	6/15%	6/13%
Spray painting/coating	8/13%	8/10%	5/10%
Processing (routing, drilling, grinding, etc.)	3/6%	5/8%	5/10%
Electronics assembly	5/10%	7/15%	10/20%
Other assembly	3/8%	3/12%	6/14%
Inspection	2/5%	4/8%	6/10%
Other	0/5%	0/5%	0/6%
	100%	100%	100%

Comments: (None)

G-3. Given the industrial robot sales projected in question G-1, how do you forecast these sales will be distributed by industry? (Note that vertical columns must necessarily total 100%).

	Median		
	Percent of Total Sales		
	1985	1990	1995
Agriculture	1%	1%	1%
Mining and extractive	1%	2%	2%
Construction	0%	1%	1%
Electricity generation	1%	1%	1%
Consumer non-durables	2%	5%	5%
Non-metal primary commodities	2%	4%	5%
Primary metals	3%	4%	5%
Non-metal fabricated commodities	5%	6%	6%
Fabricated metal products	10%	8%	8%
Machinery	8%	10%	11%
Electronics and precision equipment	8%	10%	16%
Automotive	51%	38%	26%
Aerospace	6%	6%	8%
Other transportation equipment	2%	3%	4%
	100%	100%*	100%*

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*May not total 100% due to rounding.

	Interquartile Range		
	Percent of Total Sales		
	1985	1990	1995
Agriculture	0/1%	1/2%	1/4%
Mining and extractive	1/1%	1/2%	1/3%
Construction	0/1%	0/1%	1/2%
Electricity generation	0/1%	1/1%	1/2%
Consumer non-durables	1/3%	2/7%	2/7%
Non-metal primary commodities	1/3%	2/5%	3/7%
Primary metals	2/5%	3/5%	2/6%
Non-metal fabricated commodities	5/8%	5/7%	5/8%
Fabricated metal products	5/10%	6/14%	5/12%
Machinery	5/10%	6/11%	8/11%
Electronics and precision equipment	7/10%	8/17%	10/18%
Automotive	40/54%	30/42%	20/35%
Aerospace	3/7%	5/9%	5/12%
Other transportation equipment	1/5%	1/6%	1/8%

Comments:

I believe that in the short term automotive will be the major users of industrial robots. I think agriculture machinery manufacturers will copy the developments made by the auto industry. Later, electronic companies will become big users.

Increasing use of robotics in areas such as aerospace and the primary metalworking industries will result in automotive sales constituting a smaller percentage of the total.

It is very difficult to predict these, but as robots become more intelligent, usage will change towards performing complex tasks.

Predictions here depend significantly on the definition of a robot.

Unmanned equipment will be more widely used in all industries, but much of it will not satisfy the current definition of a robot.

1985 dependent on advancement in technology.

G-4. According to U.S. government data, the average cost of a robot sold by U.S. robot producers in 1983 was approximately $42,000. In real 1983 dollars (i.e., MINUS INFLATION), what do you forecast will be the average price of a typical new robot of each of the following types in the following years? (This price is just for the robot including controls and standard tooling, but should not include ancillary equipment.)

	Median Price in 1983 Dollars (thousands)		
	1985	1990	1995
All robots, average	$42	$40	$38
Machine tending	$35	$37	$31
Material transfer (excl. machine tending)	$36	$38	$35
Spot welding	$60	$58	$50
Arc welding	$60	$60	$58
Spray painting/coating	$60	$60	$60
Processing (routing, drilling, grinding, etc.)	$45	$50	$59
Electronics assembly	$35	$40	$32
Other assembly	$35	$35	$35
Inspection	$52	$50	$50
Other	$40	$38	$40

	Interquartile Range Price in 1983 Dollars (thousands)		
	1985	1990	1995
All robots, average	$40/48	$38/45	$36/42
Machine tending	$32/45	$33.25/45	$30/40
Material transfer (excl. machine tending)	$35/50	$33.25/47	$31/50
Spot welding	$50/75	$50/71.25	$40/75
Arc welding	$50/85	$55/80	$50/75
Spray painting/coating	$50/70	$54/65	$51/60
Processing (routing, drilling, grinding, etc.)	$40/70	$40/70	$40/70
Electronics assembly	$30/45	$32/55	$27/55
Other assembly	$30/50	$30/45	$30/50
Inspection	$50/75	$50/70	$45.1/60
Other	$12/40	$12/40	$36/45

Comments:

Mix of robot types in market will serve to weight price averages.

Due to added sensory capability.

As use of robots increases in assembly, average cost will come down.

Assembly robots will be inherently more expensive because of the required sensory interfaces, enhanced programming capability, and increasd accuracy.

Estimate a 5%/year cost reduction for five years, then, generally, no decrease or increase.

In all above cases, there will be 2 classes: routine use (costs will drop); non-routine use (costs will remain about the same, but performance will increase).

Less distinction between types as controls become more powerful.

Overall prices will decrease as technology matures and competition increases.

Would expect production runs due to the aid of robots will bring the price down faster than inflation goes up.

Prices will increase in 1990 due to sensory capabilities of robots to do jobs it could not do in past. This will increase price.

G-5a. What percent of all industrial robots purchased in the U.S. will be individual stand-alone units, and what percent will be incorporated into systems or manufacturing cells?

	Median		
	1985	1990	1995
Stand-alone units	60%	50%	30%
Systems/cells	40%	50%	70%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Stand-alone units	50/73%	40/50%	25/40%
Systems/cells	27/50%	50/60%	60/75%

Comments:

By whom? All robots are part of some system.

Increased use of robots in cells or systems requires off-line programming and interdevice computer communication. These capabilities are in their embryonic stages of growth.

If labor cost is stabilized the figures for cells may be even less.

Stand-alone implies a robot that is added to a plant with no other equipment changed.

As users get burned by inexperienced systems houses they will turn to robot vendors for their complete systems and reduce their risk.

G-5b. What percent of the total value of systems or cells incorporating robots purchased in the U.S. will the robot(s) constitute, by robot type?

	Median Robot as a Percent of System Value		
	1985	1990	1995
All robots, average	50%	40%	32%
Machine tending	50%	40%	40%
Material transfer (excl. machine tending)	50%	50%	50%
Spot welding	50%	40%	41%
Arc welding	50%	50%	45%
Spray painting/coating	60%	60%	60%
Processing (routing, drilling, grinding, etc.)	40%	35%	40%
Electronics assembly	30%	33%	34%
Other assembly	35%	30%	30%
Inspection	45%	40%	38%
Other	50%	35%	30%

	Interquartile Range		
	Robot as a Percent of System Value		
	1985	1990	1995
All robots, average	45/50%	30/40%	30/45%
Machine tending	40/50%	35/45%	22/45%
Material transfer (excl. machine tending)	20/50%	30/50%	10/50%
Spot welding	40/50%	40/50%	40/50%
Arc welding	40/55%	35/55%	40/60%
Spray painting/coating	60/65%	50/60%	35/60%
Processing (routing, drilling, grinding, etc.)	35/45%	35/45%	35/45%
Electronics assembly	25/40%	25/50%	25/50%
Other assembly	20/40%	20/40%	22/35%
Inspection	30/45%	35/50%	20/45%
Other	30/60%	30/60%	30/40%

Comments:

Assembly, HDE, and arc welding applications in cell configurations should increase with the advent of improved interactive sensors and computer control systems.

Totals indicate an increase in "accessory" automated equipment used with robots.

The robot will be taking on more duties, but its cost will be decreasing.

1990 will see base price of robots go down, but sensory options/add-ons will increase package price as robots do more jobs. 1995 too far in future to determine.

Cells could include a number of pieces of equipment and one robot in which case robot would be very small percent. Above assumes simpler cells, i.e., a robot and equipment directly supported, e.g., arc welding.

G-5c. Aside from the cost of the robot system itself, there are also initial costs associated with planning, integration, and installation. What do you see these costs to be, expressed as a percentage of system cost?

	Median Initial Labor as a % of System Value		
	1985	1990	1995
All industry	40%	35%	30%

	Interquartile Range Initial Labor as a % of System Value		
	1985	1990	1995
All industry	25/50%	25/50%	20/50%

Comments:

More effort will be put into planning, including the use of process simulation software, graphics, and the like.

Cost will rise with complexity.

Expect software costs proportionately to increase.

Depends upon company structure and dependency on outside consultant.

By 1995, robots will be obsolete.

Includes all pre-planning, layout, etc.

Assumed users' labor cost.

As automation technology matures, especially CAD/CAM/DNC - percents should go down for robots, but not for total systems.

Reduced cost due to increased utilization of CAD/CAM.

Familiarity should reduce %.

Planning, integration, and installation will increase with more complex systems in general and more assembly applications.

G-6. What percent of all industrial robot purchases in the U.S. will be made directly from robot manufacturers, what percent from licensed distributors, and what percent from independent "systems houses"?

	Median		
	1985	1990	1995
Robot manufacturers	63%	55%	53%
Licensed distributors	26%	30%	26%
Systems houses	11%	15%	21%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Robot manufacturers	60/75%	50/70%	40/60%
Licensed distributors	15/30%	20/30%	20/40%
Systems houses	10/20%	10/25%	10/30%

Comments:

As experience base increases and technology matures, independent distributors, where variety of robots are displayed, will become more attractive.

Customers want single-source responsibility and system capability.

Distributors include U.S. fronts for foreign manufacturers.

Users will begin to employ the services of "systems" people to assist in the integration of robots into the factory.

G-7. What percent of industrial robots will be procured as a "turn-key package,", including layout, robot supply, and installation all from one source; and what percent will be procured on an individual basis, with purchaser assuming layout and integration responsibilities, and vendor performing only installation?

	Median		
Vendor providing:	1985	1990	1995
Total "turn-key" package	40%	50%	50%
Robot and installation only	60%	50%	50%
	100%	100%	100%

	Interquartile Range		
Vendor providing:	1985	1990	1995
Total "turn-key" package	20/60%	40/70%	40/70%
Robot and installation only	40/70%	30/60%	30/60%

Comments:

Depends on economy.

Increasing complexity - more purchased expertise.

System complexity may limit end user's ability to set up and install.

Turn-key package vendors would break initial ice in getting acceptance of robot.

Users will be progressing up the learning curve from 1990-1995.

G-8a. A recent U.S. International Trade Commission report (December 1983) estimates that nearly 18% of robot sales in 1983 were of imported robots. What percent of robots purchased by U.S. manufacturing companies for the years shown below will be foreign-built, and what percent will be U.S.-built (on a dollar volume basis)?

	Median		
	1985	1990	1995
Foreign	37%	40%	40%
U.S.	63%	60%	60%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Foreign	25/50%	30/50%	25/50%
U.S.	50/75%	50/70%	50/75%

Comments:

Cost, special features, service, length of operation, etc. constitute many features. Individual users will determine what fits best.

Totals reflect sales of less complex "robots" from foreign companies.

I can't believe U.S. will sit on their hands.

Depends on government policies.

Foreign-built includes robots built in U.S. locations by foreign companies.

This percentage must not count robot sold through U.S. robotic companies--e.g., GMF. Robot may be foreign but the system is American.

G-8b. What percent of all industrial robot units produced abroad and imported by U.S. firms will originate from the following countries?

	Median		
	% of Unit Imports		
Robots from:	1985	1990	1995
Japan	69%	61%	54%
Korea	0%	2%	3%
Other Asia	0%	0%	1%
Canada	0%	0%	0%
Australia	0%	0%	0%
Western Europe*	28%	31%	33%
All other foreign	3%	6%	9%
	100%	100%	100%

*includes Scandinavia

	Interquartile Range		
	% of Unit Imports		
Robots from:	1985	1990	1995
Japan	60/75%	50/66%	40/60%
Korea	0/2%	0/5%	0/6%
Other Asia	0/1%	0/5%	0/5%
Canada	0/2%	0/3%	0/4%
Australia	0/1%	0/2%	0/3%
Western Europe*	20/30%	25/30%	20/35%
All other foreign	0/7%	0/9%	3/13%

*includes Scandinavia

Comments:

Japan would be major outside source.

Politics will be a factor.

G-8c. What type(s) of imported robots will be most in demand?

	Percent of Responses					
	1985		1990		1995	
	Most	2nd Most	Most	2nd Most	Most	2nd Most
Material transfer	48%	15%	23%	36%	12%	48%
Spot welding	7%	4%	0%	0%	0%	0%
Arc welding	26%	18.5%	11%	20%	8%	13%
Spray painting	4%	18.5%	0%	16%	4%	9%
Other finishing & processing	0%	7%	0%	0%	0%	4%
Electronics assembly	0%	7%	8%	4%	4%	4%
Other assembly	11%	26%	58%	16%	64%	9%
Inspection	0%	0%	0%	8%	4%	4%
Other	4%	4%	0%	0%	4%	9%
	100%	100%	100%	100%	100%	100%

Comments:

A general trend of importing low-level robotics will prevail through the projected period.

Imports will be standard units - exports will be specials.

Growing intelligence through period.

G-9a. According to the ITC report, total U.S. robot exports equalled approximately 117% of total U.S. imports in 1983. What will this percentage of exports-to-imports be in the following years?

	Median		
	1985	1990	1995
Robot exports-to-imports	100%	90%	90%

	Interquartile Range		
	1985	1990	1995
Robot exports-to-imports	90/120%	85/120%	75/140%

Comments:

Will depend upon cost control and improvements in design features and manufacturing.

Need much more attention to application, not robot development.

Numbers in question must not count dollar volume of import and exports.

Robots may be imported, incorporated into systems, and then exported as part of the systems.

G-9b. What type(s) of exported robots will be most in demand?

	Percent of Responses					
	1985		1990		1995	
	Most	2nd Most	Most	2nd Most	Most	2nd Most
Material transfer	41%	26%	20%	35%	16%	50%
Spot welding	5%	5%	0%	0%	0%	0%
Arc welding	18%	11%	20%	12%	11%	13%
Spray painting	9%	11%	0%	12%	5%	6%
Other finishing & processing	5%	5%	5%	12%	11%	6%
Electronics assembly	0%	5%	10%	0%	5%	0%
Other assembly	13%	26%	30%	17%	42%	6%
Inspection	5%	11%	5%	12%	5%	0%
Other	5%	0%	10%	0%	5%	19%
	100%*	100%	100%	100%	100%	100%

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*May not total 100% due to rounding.

Comments:

A general trend of exporting high level robotics with advanced capabilities will prevail through the projection period.

Imports will be standard units - exports will be specials.

G-10a. For those robot procurements imported from all foreign robot manufacturing sources into the U.S., rank (from 1 to 8) the following factors in order of importance (1 = most important).

	Median Ranking		
	1985	1990	1995
Purchase cost advantage	1	1	1
Robot design features	3	3	3
Performance	2	2	2
Superior maintenance	4	4	4
Better warranties	6	6	6
Favorable finance terms	7	7	7
Other	8	8	8

	Interquartile Range Ranking		
	1985	1990	1995
Purchase cost advantage	1/3	1/3	1/3
Superior delivery	4/5	6/4	3/6
Robot design features	2/4	2/3	2/4
Performance	1/3	1/3	1/3
Superior maintenance	4/5	4/5	3/5
Better warranties	5/6	5/6	5/6
Favorable finance terms	5/7	6/7	5/7
Other	8/8	8/8	8/8

Comments:

Same criteria for all robots today, domestic and imported.

G-10b. For those foreign procurements of robots exported by U.S. robot makers, rank (from 1 to 8) the following factors in order of importance (1 = most important).

	Median Ranking		
	1985	1990	1995
Purchase cost advantage	4	3	4
Superior delivery	6	5	5
Robot design features	1	2	2
Performance	2	2	2
Superior maintenance	4	4	4
Better warranties	5	5	5
Favorable finance terms	6	6	6
Other	8	8	8

	Interquartile Range Ranking		
	1985	1990	1995
Purchase cost advantage	2/6	2/5	2/6
Superior delivery	5/7	4/6	4/6
Robot design features	1/2	1/3	1/3
Performance	1/2	1/2	1/2
Superior maintenance	3/6	3/5	3/5
Better warranties	4/6	4/6	4/6
Favorable finance terms	4/7	5/7	5/7
Other	7/8	7/8	7/8

Comments: (None)

G-10c. Of all industrial robots in operation in the U.S. in each of the following years, how will they be distributed geographically?

	Median		
	1985	1990	1995
New England (ME, NH, VT, MA, RI, CT)	10%	11%	11%
Mid-Atlantic (NY, PA, NJ)	10%	11%	10%
South Atlantic (DE, MD, DC, VA, WV, NC, SC, GA, FL)	8%	9%	9%
East North Central (OH, MI, IN, IL, WI)	40%	34%	28%
West North Central (MN, IA, MO, ND, SD, NE, KS)	5%	5%	6%
East South Central (KY, TN, MS, AL)	5%	5%	6%
West South Central (AR, LA, OK, TX)	5%	5%	7%
Mountain (MT, WY, CO, NM, ID, UT, AZ, NV)	5%	5%	6%
Pacific (CA, OR, WA, AK, HI)	12%	15%	17%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
New England (ME, NH, VT, MA, RI, CT)	5/11%	5/11%	5/11%
Mid-Atlantic (NY, PA, NJ)	8/15%	5/12%	5/10%
South Atlantic (DE, MD, DC, VA, WV, NC, SC, GA, FL)	5/10%	5/14%	5/15%
East North Central (OH, MI, IN, IL, WI)	17/50%	20/40%	20/40%
West North Central (MN, IA, MO, ND, SD, NE, KS)	2/6%	3/8%	4/10%
East South Central (KY, TN, MS, AL)	3/5%	3/5%	5/7%
West South Central (AR, LA, OK, TX)	5/10%	5/10%	5/10%
Mountain (MT, WY, CO, NM, ID, UT, AZ, NV)	2/5%	2/8%	4/8%
Pacific (CA, OR, WA, AK, HI)	8/17%	10/16%	10/17%

Comments: (None)

G-11. What will be the average after-tax payback period (in years) experienced by U.S. industry in the aggregate for robots installed in the years shown?

	Median Ranking		
	1985	1990	1995
All industry	3	3	2.1

	Interquartile Range Ranking		
	1985	1990	1995
All industry	2.5/4	2.5/3	2/3

Comments:

Expect labor cost increases to be moderate in future, and so is desirability of robot applications.

Industry maturing; cream of quick payout skimmed.

Not that simple; most will be in systems and 2 years could be good for major system.

Payback includes system robots will be part of.

Payback to what? Survival or operating costs? Most lines should be replaced every 3-5 years just to remain in business. Commonly held cost accounting standards do not apply to many robots.

Revision of tax laws would help greatly.

Experience and reduced cost should lower payback. That is primary reason for increased sales.

G-12. What do you forecast will be the average after-tax payback period (in years) experienced by robot users, depending on the type of robot for units installed in the years shown?

	Median Ranking		
	1985	1990	1995
Machine tending	3	2.5	3
Material transfer (excl. machine tending)	3	2.5	2.5
Spot welding	2.5	2.3	2.1
Arc welding	2.5	2.3	2.5
Spray painting/coating	3	2.5	2.1
Processing (routing, drilling, grinding, etc.)	3	3	3
Electronics assembly	3	3	3
Other assembly	3	3	3
Inspection	3	2.5	2.5
Other	3	3	2.5

	Interquartile Range Ranking		
	1985	1990	1995
Machine tending	2/3	2.3/3	2/3
Material transfer (excl. machine tending)	2/3	2.5/3	2/3
Spot welding	2/3	2/3	2/3
Arc welding	2/3	2/3	2/3
Spray painting/coating	2/3	2/3	2/3
Processing (routing, drilling, grinding, etc.)	2/3.5	2/3	2/3
Electronics assembly	2.5/3.5	2.5/3	2/3
Other assembly	2.5/3	2.5/3	2/3
Inspection	2/3	2/3	2/3
Other	3/3	3/3	2.5/3

Comments:

Again, assuming robots as stand-alone units, and it is not clear that that will be typical.

Based on labor.

The easy jobs will get done the first years, the more complicated will be done later, thus it will cost more, and the payback period will be longer.

Too many hidden costs; the Japanese can live with long paybacks, the U.S. won't.

G-13. Lately, there have been many calls for federal government action to enhance U.S. industrial productivity through the greater use of flexible automation. Ten commonly raised suggestions are listed below. Rank [from 1 to 5] the degree of usefulness of positive government action on each. (1 = very useful).

	Median Ranking
Direct funding and promotion of R&D	2
Relaxation of antitrust laws to permit joint corporate R&D	2
Development of government-sponsored robot leasing program	4
Accelerated depreciation for robotic equipment	2
Direct tax breaks for robot purchasers	2
Government robotic information clearinghouse and/or data bank	3
Establishment of an Industrial Policy Agency	4
Export subsidies or other benefits	3
Increase in secondary and college-level educational expenditures	2
Establishment of government retraining programs for displaced workers	3

	Interquartile Range
Direct funding and promotion of R&D	1/3
Relaxation of antitrust laws to permit joint corporate R&D	1/3
Development of government-sponsored robot leasing program	3/5
Accelerated depreciation for robotic equipment	1/2
Direct tax breaks for robot purchasers	1/3
Government robotic information clearinghouse and/or data bank	3/4
Establishment of an Industrial Policy Agency	3/5
Export subsidies or other benefits	3/5
Increase in secondary and college-level educational expenditures	1/3
Establishment of government retraining programs for displaced workers	2/4

Comments:

Establishment of government retraining programs is very important. Government required industry's training programs. Government should give breaks to those who retrain instead of hiring or laying off.

Are subsidies "breaks" or "payments"? This is unclear.

Let industry apply technology where appropriate.

This is not a government responsibility.

G-13a. Lately, there have been many calls for federal government action to enhance U.S. productivity through the greater use of automation. In Round I, ten commonly raised suggestions were listed, with respondents requested to rank the degree of usefulness of each. In this round, we have added five more. As before, please rank their degree of usefulness if enacted. (1=Very Useful, 5=Not at All Useful)

	Median Ranking
Federal government procurement of newly introduced robot products to reinforce initial demand.	4
Special programs to assist small suppliers to the robotics industry in obtaining financial backing.	3
Government-sponsored low-interest loans to potential robotics or other automation purchasers.	2
Trade protection measures on behalf of the robotics industry.	4
Reestablishment of the Nixon Administration's National Productivity Center to conduct research into productivity enhancement.	3

	Interquartile Range
Federal government procurement of newly introduced robot products to reinforce initial demand.	3/4
Special programs to assist small suppliers to the robotics industry in obtaining financial backing.	2/4
Government-sponsored low-interest loans to potential robotics or other automation purchasers.	1/3
Trade protection measures on behalf of the robotics industry.	3/5
Reestablishment of the Nixon Administration's National Productivity Center to conduct research into productivity enhancement.	2/4

Comments: (None)

G-14. List the technological barriers that represent constraints to the more rapid utilization of robots by U.S. industry. Please be as specific as possible.

	% of Responses
Non-vision sensory systems	18%
Programming limitations/lack of standards	14
Control system limitations/lack of standards	11
Communications limitations/lack of compatability with other equipment	8
Tooling limitations/lack of standards	6
Vision systems	5
Software limitations	2
Maintenance/troubleshooting	2
Lack of artificial intelligence	1
Computer limitations	1
Repeatability/accuracy	1
Speed	1
Mobility	1
Teaching systems	1
Protection from harsh environments	1
Remote control of isolated robots	1
Payload limitations of electric robots	1
Reliability of weld trackers	1
Flexibility of applications	1
Safety barrier technology	1
Handling of flexible objects	1
Parts presentation	1
Poor designs	1
"Standards"	1
Other, nontechnological (costs, training, etc.)	16
No technological barriers	2
	100%

Comments:

Major problem is management, not technology.

No technical barriers - U.S. industry needs to use what we already have.

There is no technology problem.

Principal limit is now management's limited technical sense of robotics application.

G-14a. Listed below are the most frequently cited technological barriers which represent current constraints to more rapid utilization of robots by U.S. manufacturers, as determined in the last Delphi round. How would you rank the severity of each barrier? (1=Critical; 5=Not a Barrier)

	Median Ranking
Vision systems	2
Non-vision sensors	3
Software limitations	2
Communication/compatibility with existing equipment	2
Computer limitations	3
Tooling limitations	3
Repeatability/accuracy	3
Speed	3
Arm oscillations	3
Mobility	3
Parts presentation requirements	3
Accident avoidance	3
Other	1

	Interquartile Range
Vision systems	2/3
Non-vision sensors	2/3
Software limitations	1/3
Communication/compatibility with existing equipment	1/3
Computer limitations	2/4
Tooling limitations	3/4
Repeatability/accuracy	2/3
Speed	2/4
Arm oscillations	2/4
Mobility	2/4
Parts presentation requirements	2/4
Accident avoidance	2/4
Other	1/3

Comments:

None of these. Most important barrier is outmoded accounting practices of U.S. industry.

G-15. Rank-order (from 1 to 8) the importance of each of the following potential performance barriers as constraints to the adoption of robotic technology by U.S. industry. (1 = most important).

	Median Ranking
Accuracy	2
Velocity	5
Repeatability	1
Load	4
Size	6
Up-time	3

	Interquartile Range Ranking
Accuracy	2/4
Velocity	3/6
Repeatability	1/4
Load	3/5
Size	4/6
Up-time	1/6

Comments: (None)

G-16a. Of all material transfer robots purchased in the U.S. in the years listed below, what will be the percentage distribution of units falling into the following load capacities?

	Median Ranking		
	Percent of Material Transfer Robot Sales		
	1985	1990	1995
0 - 5 lbs.	14%	20%	23%
5.1 - 10 lbs.	14%	17%	18%
10.1 - 20 lbs.	14%	17%	18%
20.1 - 40 lbs.	30%	17%	11.5%
40.1 - 60 lbs.	14%	12%	11.5%
Over 60 lbs.	14%	17%	18%
	100%	100%	100%

	Interquartile Range Ranking Percent of Material Transfer Robot Sales		
	1985	1990	1995
0 - 5 lbs.	1/20%	5/35%	10/33%
5.1 - 10 lbs.	5/20%	5/20%	5/20%
10.1 - 20 lbs.	5/20%	8/23%	7/20%
20.1 - 40 lbs.	10/35%	7/20%	7/20%
40.1 - 60 lbs.	4/20%	5/15%	5/15%
Over 60 lbs.	5/30%	4/20%	2/30%

Comments:

Heavy load capacity robots should increase in use for handling large castings and other large products.

Expect more intricate precision assembly, etc., operations.

G-16b. Of all finishing and processing robots purchased in the U.S. in the years listed below, what will be the percentage distribution of units falling into the following load capacities?

	Median		
	1985	1990	1995
0 - 5 lbs.	17%	12%	8%
5.1 - 10 lbs.	17%	25%	25%
10.1 - 20 lbs.	34%	31%	31%
20.1 - 40 lbs.	20%	20%	20%
40.1 - 60 lbs.	6%	6%	8%
Over 60 lbs.	6%	6%	8%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
0 - 5 lbs.	0/20%	0/25%	0/25%
5.1 - 10 lbs.	0/20%	0/25%	5/35%
10.1 - 20 lbs.	2/35%	2/35%	2/35%
20.1 - 40 lbs.	10/24%	10/29%	8/25%
40.1 - 60 lbs.	0/9%	0/8%	0/10%
Over 60 lbs.	2/10%	1/10%	3/10%

Comments:

Auxiliary equipment, (i.e., conveyors) will be presenting parts to robot for finishing.

Weight handling is an insignificant characteristic of a finishing robot.

G-16c. Of all electronics assembly robots purchased in the U.S. in the years listed below, what will be the percentage distribution of units falling into the following load capacities?

	Median		
	1985	1990	1995
0 - 0.5 lbs.	45%	47%	40%
0.51 - 1.0 lbs.	23%	21%	24%
1.1 - 3.0 lbs.	17%	18%	20%
3.1 - 5.0 lbs.	9%	9%	11%
Over 5.0 lbs.	6%	5%	5%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
0 - 0.5 lbs.	10/60%	5/80%	15/80%
0.51 - 1.0 lbs.	10/25%	10/25%	10/25%
1.1 - 3.0 lbs.	8/20%	8/25%	8/25%
3.1 - 5.0 lbs.	1/10%	1/10%	1/15%
Over 5.0 lbs.	0/20%	0/15%	1/15%

Comments:

Boards are light!

Projection assumes advances on VLSI.

Trends in electronics toward smaller, lighter equipment will be balanced by new packaging.

G-16d. Of all other assembly robots purchased in the U.S. in the years listed below, what will be the percentage distribution of units falling into the following load capacities?

	Median		
	1985	1990	1995
0 - 5 lbs.	41%	32%	33%
5.1 - 10 lbs.	22%	24%	23%
10.1 - 20 lbs.	18%	22%	22%
20.1 - 40 lbs.	9%	11%	12%
40.1 - 60 lbs.	5%	6%	5%
Over 60 lbs.	5%	5%	5%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
0 - 5 lbs.	25/50%	10/44%	10/44%
5.1 - 10 lbs.	15/30%	12/30%	15/30%
10.1 - 20 lbs.	12/30%	15/25%	15/28%
20.1 - 40 lbs.	6/20%	8/20%	10/18%
40.1 - 60 lbs.	0/10%	3/10%	3/15%
Over 60 lbs.	0/10%	0/11%	1/12%

Comments: (None)

G-17. Of all "light load" (5 lbs. and under) capacity robots purchased in the U.S., what will be the market shares of those in each weight category?

	Median		
	1985	1990	1995
0 - 0.5 lb.	5%	10%	10%
0.51 - 1.0 lb.	15%	21%	26%
1.1 - 3 lbs.	30%	28%	28%
3.1 - 5 lbs.	50%	41%	36%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
0 - 0.5 lb.	0/16%	0/15%	0/20%
0.51 - 1.0 lb.	10/30%	10/30%	10/30%
1.1 - 3 lbs.	10/30%	10/38%	10/35%
3.1 - 5 lbs.	25/50%	28/50%	28/50%

Comments: (None)

G-18. What will be the typical accuracies (in inches) of robots used for electronic assembly?

	Median		
	Accuracy		
	1985	1990	1995
Electronics assembly	.002	.001	.001

	Interquartile Range		
	Accuracy		
	1985	1990	1995
Electronics assembly	.001/.005	.0005/.002	.0002/.002

Comments:

Not repeatability!

Will probably have to be accurate enough to fix flaws in micro chips.

Repeatability is the measurement that should be used.

G-19. What will be the typical accuracies (in inches) of large-capacity (100 lbs. or more) robots?

	Median		
	Accuracy		
	1985	1990	1995
All industry	.04	.025	.02

	Interquartile Range		
	Accuracy		
	1985	1990	1995
All industry	.04/.06	.01/.05	.005/.03

Comments: (None)

G-20a. What percent of all industrialized robots operating in the U.S. will utilize commercial computer time-sharing services for their robot programming requirements?

	Median		
	1985	1990	1995
All industry	5%	10%	15%

	Interquartile Range		
	1985	1990	1995
All industry	1/10%	5/15%	10/40%

Comments:

In 1995, they will use artifical intelligence.

Computer-controlled robots will negate this need.

This is of extreme importance. This ability and the software to support it should be required and standard.

Most end users will program in-house, using microcomputers with commercial or self-generated software.

Time sharing is too costly compared to microcomputers.

It will be possible to buy microcomputers for simple tasks--depends on the growth of computer technology.

G-20b. What percent of all industrial robots operating in the U.S. will be leased, rather than owned, by the user?

	Median		
	1985	1990	1995
All industry	5%	10%	15%

	Interquartile Range		
	1985	1990	1995
All industry	1/5%	5/10%	5/15%

Comments: (None)

G-21. At the close of 1982, there were approximately 6,800 robots installed in the U.S. How many of these do you forecast will still be operating in the following years?

	Median			
	1985	1990	1995	2000
All industry	90%	70%	30%	10%

	Interquartile Range			
	1985	1990	1995	2000
All industry	80/95%	50/75%	20/50%	5/20%

Comments:

They will be replaced by better systems - technology obsolesces.

Includes robots still usable, but taken out of service due to changes in production.

Many load/unload robots will not see technological obsolescence prior to the end of their serviceable life.

The projections are for those original 6,800.

The robots will not wear out, but be replaced by newer robot technology.

G-22. What are the current voids in hardware or system capabilities (e.g., a 50 lb., .001 inch accurate arm does not exist)?

	% of Responses
Sensor limitations	15
Payload weight limitations	12
Speed limitations	12
Accuracy/repeatability limitations	12
Gripper limitations	7
Stronger, lighter arm	5
Extended reach	5
Gripper limitations	5
Adequate software	5
Robot size	5
Motor improvements	2
Controller limitations	2
Integration	2
Multiple arms	2
Response in hazardous work areas	2
Other, non-technical (cost, "need")	7
	100%

Comments: (None)

G-22a. Listed below are the most frequently cited current voids in robot hardware, as determined in the last Delphi round. How would you rank the importance of alleviating each shortcoming? (1 = Critical; 5 = Not important)

	Ranking Median
Inadequate non-vision sensors	2
Payload weight limitations of electric robots	3
Stronger, lighter arm	2
Extended reach	3
Gripper limitations	3
Arm oscillations/dampening	3
Robot size	3
Multiple arms	3
Motor limitations	3
Other	1

	Ranking Interquartile Range
Inadequate non-vision sensors	2/3
Payload weight limitations of electric robots	2/3
Stronger, lighter arm	2/3
Extended reach	2/4
Gripper limitations	2/3
Arm oscillations/dampening	2/3
Robot size	2/4
Multiple arms	3/4
Motor limitations	2/3
Other	1/1

Comments: (None)

G-23. What will be the approximate dollar-volume market shares of the major U.S.-based robot vendors in the next five years?

	Median		
	1983 Actual	1985	1988
Cincinnati Milacron	21.3%	19%	16%
Westinghouse/Unimation	15.0	13%	11%
GMFanuc	9.2	13%	15%
DeVilbiss	8.8	9%	7%
ASEA	6.3	7%	8%
Prab	5.6	5%	6%
Automatix	5.4	5%	6%
General Electric	4.6	6%	9%
IBM	3.8	4%	4%
GCA	2.5	3%	3%
All Others	26.5	16%	15%
	100.0%	100%	100%

	Interquartile Range	
	1985	1988
Cincinnati Milacron	16/20%	15/18%
Westinghouse/Unimation	10/15%	8/12%
GMFanuc	10/17%	12/20%
DeVilbiss	7/10%	5/8%
ASEA	5/8%	5/10%
Prab	5/6%	5/7%
Automatix	5/6%	5/7%
General Electric	5/7%	7/10%
IBM	3/5%	4/7%
GCA	3/3%	2/3%
All Others	11/20%	4/15%

Comments:

"Other" category will increasingly be composed of small suppliers of highly specialized equipment.

GE will grow quickly.

Might be some question of whether GMF is really a U.S. vendor.

Unimation's position should be enhanced by the Westinghouse take-over. Cybotech and GCA are coming on strong.

G-24. The following set of questions is designed to forecast robot trends, by industry. Several industries were determined satisfactorily in the last round; several more remain to be settled. We realize that to answer all the questions in the set (G-24e through G-24n) would be a substantial undertaking. Thus, we ask that you provide answers for ONLY THOSE INDUSTRIES that you feel your expertise allows. Definitions for each of these industries can be found on the last page of the questionnaire.

G-24a. What percent of all industrial robot units purchased by companies in agriculture will be in the following application areas?

	Median Percent of Agricultural Applications 1983	 1990	 1995
Material transfer/machine tending	56%	62%	67%
Spot welding	0%	0%	0%
Arc welding	19%	15%	13%
Spray painting	19%	15%	13%
Other finishing & processing	0%	0%	0%
Electronics assembly	0%	0%	0%
Other assembly	0%	0%	0%
Inspection	6%	8%	7%
Other	0%	0%	0%

	Interquartile Range Percent of Agricultural Applications 1983	 1990	 1995
Material transfer/machine tending	5/70%	10/70%	5/70%
Spot welding	0/1%	0/1%	0/1%
Arc welding	0/60%	0/50%	0/40%
Spray painting	0/20%	0/20%	0/20%
Other finishing & processing	0/0%	0/0%	0/0%
Electronics assembly	0/0%	0/0%	0/0%
Other assembly	0/0%	0/1%	0/0%
Inspection	0/8%	5/10%	0/10%
Other	0/0%	0/0%	0/0%

Comments: (None)

G-24b. What percent of all industrial robot units purchased by companies in the mining and extractive industries will be in the following application areas?

	Median Percent of Mining Applications 1983	 1990	 1995
Material transfer/machine tending	100%	100%	100%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting	0%	0%	0%
Other finishing & processing	0%	0%	0%
Electronics assembly	0%	0%	0%
Other assembly	0%	0%	0%
Inspection	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Mining Applications 1983	 1990	 1995
Material transfer/machine tending	10/100%	15/100%	25/100%
Spot welding	0/0%	0/0%	0/0%
Arc welding	0/25%	0/20%	0/15%
Spray painting	0/10%	0/10%	0/10%
Other finishing & processing	0/5%	0/5%	0/4%
Electronics assembly	0/0%	0/0%	0/0%
Other assembly	0/0%	0/0%	0/0%
Inspection	0/5%	0/5%	0/4%
Other	0/0%	0/0%	0/5%

Comments: (None)

G-24c. What percent of all industrial robot units purchased by companies in the construction industry will be in the following application areas?

	Median Percent of Construction Applications 1983	 1990	 1995
Material transfer/machine tending	67%	73%	73%
Spot welding	0%	0%	0%
Arc welding	11%	9%	9%
Spray painting	22%	18%	18%
Other finishing & processing	0%	0%	0%
Electronics assembly	0%	0%	0%
Other assembly	0%	0%	0%
Inspection	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Construction Applications 1983	 1990	 1995
Material transfer/machine tending	10/80%	10/80%	10/80%
Spot welding	0/0%	0/0%	0/0%
Arc welding	5/20%	5/20%	5/20%
Spray painting	0/25%	0/20%	0/20%
Other finishing & processing	0/0%	0/0%	0/0%
Electronics assembly	0/0%	0/0%	0/0%
Other assembly	0/0%	0/0%	0/0%
Inspection	0/0%	0/0%	0/0%
Other	0/0%	0/0%	0/0%

Comments: (None)

G-24d. What percent of all industrial robot units purchased by companies in the electricity-generating industry will be in the following application areas?

	Median		
	Percent of Electricity Generation Applications		
	1983	1990	1995
Material transfer/machine tending	72%	61%	57%
Spot welding	0%	0%	0%
Arc welding	2%	4%	8%
Spray painting	3%	3%	3%
Other finishing & processing	16%	16%	17%
Electronics assembly	3%	5%	5%
Other assembly	2%	4%	7%
Inspection	2%	7%	3%
Other	0%	0%	0%

	Interquartile Range		
	Percent of Electricity Generation Applications		
	1983	1990	1995
Material transfer/machine tending	0/89%	0/79%	0/68%
Spot welding	0/0%	0/0%	0/0%
Arc welding	0/2%	0/5%	0/10%
Spray painting	0/7%	0/13%	0/4%
Other finishing & processing	0/20%	0/20%	0/20%
Electronics assembly	1/25%	4/25%	4/25%
Other assembly	0/2%	0/10%	0/8%
Inspection	2/55%	3/55%	2/55%
Other	0/0%	0/0%	0/0%

Comments: (None)

G-24e. What percent of all industrial robot units purchased by companies in the consumer non-durables industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	21%	21%	22%
Material transfer (excl. machine tending)	31%	25%	19%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting/coating	0%	4%	4%
Processing (routing, drilling, grinding, etc.)	6%	8%	9%
Electronics assembly	11%	11%	9%
Other assembly	21%	21%	22%
Inspection	10%	10%	15%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/26%	10/25%	10/25%
Material transfer (excl. machine tending)	10/80%	10/60%	10/40%
Spot welding	0/10%	0/16%	0/14%
Arc welding	0/5%	0/18%	0/18%
Spray painting/coating	0/5%	0/8%	0/6%
Processing (routing, drilling, grinding, etc.)	0/6%	0/12%	0/15%
Electronics assembly	1/18%	1/15%	1/12%
Other assembly	6/25%	5/25%	5/27%
Inspection	2/10%	1/10%	1/17%
Other	0/20%	0/4%	0/5%

Comments: (None)

G-24f. What percent of all industrial robot units purchased by companies in the non-metal primary commodity industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	14%	16%	20%
Material transfer (excl. machine tending)	29%	42%	27%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting/coating	28%	16%	10%
Processing (routing, drilling, grinding, etc.)	19%	14%	19%
Electronics assembly	1%	4%	6%
Other assembly	3%	3%	8%
Inspection	7%	5%	10%
Other	0%	0%	0%
	100%*	100%	100%

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*May not total 100% due to rounding.

	Interquartile Range		
	1985	1990	1995
Machine tending	5/15%	13/27%	15/27%
Material transfer (excl. machine tending)	10/40%	21/50%	20/35%
Spot welding	0/1%	0/1%	0/1%
Arc welding	0/0%	0/0%	0/0%
Spray painting/coating	4/40%	5/30%	5/15%
Processing (routing, drilling, grinding, etc.)	5/25%	10/20%	14/22%
Electronics assembly	0/12%	0/12%	0/12%
Other assembly	0/13%	0/12%	0/11%
Inspection	2/12%	4/9%	10/11%
Other	0/0%	0/0%	0/0%
	100%	100%	100%

Comments: (None)

G-24g. What percent of all industrial robot units purchased by companies in the primary metals industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	20%	22%	17%
Material transfer (excl. machine tending)	30%	31%	36%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting/coating	0%	0%	0%
Processing (routing, drilling, grinding, etc.)	40%	38%	36%
Electronics assembly	0%	0%	0%
Other assembly	0%	0%	0%
Inspection	10%	9%	11%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	0/30%	5/30%	10/20%
Material transfer (excl. machine tending)	10/40%	14/40%	14/40%
Spot welding	0/0%	0/0%	0/0%
Arc welding	0/0%	0/0%	0/0%
Spray painting/coating	0/0%	0/0%	0/0%
Processing (routing, drilling, grinding, etc.)	20/50%	20/50%	20/40%
Electronics assembly	0/0%	0/0%	0/0%
Other assembly	0/0%	0/0%	0/0%
Inspection	5/10%	5/10%	7/15%
Other	0/20%	0/20%	0/0%

Comments: (None)

G-24h. What percent of all industrial robot units purchased by companies in the non-metal fabricated commodities industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	28%	35%	34%
Material transfer (excl. machine tending)	72%	58%	59%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting/coating	0%	0%	0%
Processing (routing, drilling, grinding, etc.)	0%	0%	0%
Electronics assembly	0%	0%	0%
Other assembly	0%	0%	0%
Inspection	0%	7%	7%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/35%	7/50%	7/50%
Material transfer (excl. machine tending)	0/80%	0/70%	0/65%
Spot welding	0/0%	0/0%	0/0%
Arc welding	0/0%	0/0%	0/0%
Spray painting/coating	0/0%	0/0%	0/0%
Processing (routing, drilling, grinding, etc.)	0/12%	0/11%	0/10%
Electronics assembly	0/0%	0/0%	0/0%
Other assembly	0/0%	0/0%	0/0%
Inspection	0/5%	0/10%	0/10%
Other	0/0%	0/0%	0/0%

Comments: (None)

G-24i. What percent of all industrial robot units purchased by companies in the fabricated metal products industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	19%	17%	17%
Material transfer (excl. machine tending)	19%	19%	17%
Spot welding	12%	11%	11%
Arc welding	12%	11%	11%
Spray painting/coating	12%	11%	7%
Processing (routing, drilling, grinding, etc.)	10%	10%	7%
Electronics assembly	3%	3%	6%
Other assembly	7%	9%	12%
Inspection	6%	9%	12%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	10/20%	10/20%	12/28%
Material transfer (excl. machine tending)	5/30%	5/20%	5/22%
Spot welding	0/20%	0/25%	0/20%
Arc welding	5/14%	5/15%	10/16%
Spray painting/coating	0/15%	5/12%	0/10%
Processing (routing, drilling, grinding, etc.)	5/15%	5/20%	1/16%
Electronics assembly	0/8%	0/9%	1/10%
Other assembly	0/12%	5/11%	10/22%
Inspection	0/9%	1/10%	2/15%
Other	0/5%	0/9%	0/5%
	100%	100%	100%

Comments: (None)

G-24j. What percent of all industrial robot units purchased by companies in the machinery manufacturing industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	14%	16%	20%
Material transfer (excl. machine tending)	29%	23%	20%
Spot welding	3%	3%	3%
Arc welding	7%	9%	11%
Spray painting/coating	11%	14%	10%
Processing (routing, drilling, grinding, etc.)	7%	8%	11%
Electronics assembly	9%	8%	7%
Other assembly	7%	8%	7%
Inspection	13%	11%	11%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/25%	10/17%	12/25%
Material transfer (excl. machine tending)	15/40%	5/35%	10/30%
Spot welding	0/5%	0/5%	0/5%
Arc welding	5/10%	5/10%	5/14%
Spray painting/coating	2/15%	3/15%	3/15%
Processing (routing, drilling, grinding, etc.)	5/20%	5/25%	4/30%
Electronics assembly	5/10%	4/10%	5/10%
Other assembly	4/10%	5/12%	5/11%
Inspection	5/15%	5/15%	5/15%
Other	0/5%	0/5%	0/5%
	100%	100%	100%

Comments: (None)

G-24k. What percent of all industrial robot units purchased by companies in the electronics and precision equipment industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	20%	20%	12%
Material transfer (excl. machine tending)	20%	20%	15%
Spot welding	0%	0%	0%
Arc welding	0%	0%	0%
Spray painting/coating	0%	0%	0%
Processing (routing, drilling, grinding, etc.)	4%	2%	6%
Electronics assembly	29%	39%	49%
Other assembly	10%	6%	6%
Inspection	17%	13%	12%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/40%	10/25%	10/20%
Material transfer (excl. machine tending)	10/30%	5/25%	5/26%
Spot welding	0/1%	0/2%	0/1%
Arc welding	0/0%	0/0%	0/0%
Spray painting/coating	0/1%	0/1%	0/2%
Processing (routing, drilling, grinding, etc.)	0/12%	1/14%	2/14%
Electronics assembly	5/42%	15/40%	33/60%
Other assembly	2/10%	1/10%	1/12%
Inspection	4/20%	3/15%	5/15%
Other	0/10%	0/10%	0/5%

Comments:

Includes limited axis units for assembly.

G-24L. What percent of all industrial robot units purchased by companies in the automotive industry will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	13%	12%	19%
Material transfer (excl. machine tending)	9%	7%	6%
Spot welding	68%	51%	35%
Arc welding	2%	6%	6%
Spray painting/coating	6%	7%	7%
Processing (routing, drilling, grinding, etc.)	0%	4%	7%
Electronics assembly	0%	3%	4%
Other assembly	2%	3%	9%
Inspection	0%	7%	7%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	2/15%	5/15%	9/20%
Material transfer (excl. machine tending)	4/14%	2/15%	3/10%
Spot welding	30/75%	25/55%	20/45%
Arc welding	1/5%	1/10%	1/8%
Spray painting/coating	2/12%	3/13%	2/13%
Processing (routing, drilling, grinding, etc.)	0/1%	0/13%	0/12%
Electronics assembly	0/3%	0/3%	0/5%
Other assembly	0/4%	2/10%	3/15%
Inspection	0/5%	3/10%	3/10%
Other	0/0%	0/0%	0/2%

Comments: (None)

G-24m. What percent of all industrial robot units purchased by companies in the aerospace industry will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	9%	13%	13%
Material transfer (excl. machine tending)	28%	19%	18%
Spot welding	0%	1%	1%
Arc welding	10%	13%	12%
Spray painting/coating	8%	12%	12%
Processing (routing, drilling, grinding, etc.)	18%	19%	18%
Electronics assembly	8%	8%	12%
Other assembly	9%	6%	6%
Inspection	10%	9%	8%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/20%	8/15%	10/15%
Material transfer (excl. machine tending)	10/30%	10/20%	12/20%
Spot welding	0/6%	0/6%	0/5%
Spray painting/coating	3/10%	7/15%	9/15%
Processing (routing, drilling, grinding, etc.)	10/33%	15/28%	15/27%
Electronics assembly	5/10%	5/10%	5/15%
Other assembly	5/10%	5/15%	0/20%
Inspection	5/10%	5/10%	7/10%
Other	0/2%	0/0%	0/0%

Comments:

Arc welding will increase as feedback control via through-the-arc sensing and seam-tracking sensors become perfected. HDE is on the upsurge. Assembly is the thrust of the future, provided that off-line programming, improved accuracy, and better sensors are made available.

This spot welding robot could fill in for drilling robots in other assembly.

G-24n. What percent of all industrial robot units purchased by companies in other transportation equipment industries will be in the following application areas?

	Median		
	1985	1990	1995
Machine tending	24%	23%	17%
Material transfer (excl. machine tending)	19%	18%	12%
Spot welding	10%	11%	12%
Arc welding	24%	25%	27%
Spray painting/coating	6%	8%	12%
Processing (routing, drilling, grinding, etc.)	5%	3%	5%
Electronics assembly	1%	2%	3%
Other assembly	5%	6%	6%
Inspection	6%	4%	6%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Machine tending	5/29%	10/25%	10/27%
Material transfer (excl. machine tending)	10/35%	10/31%	6/15%
Spot welding	5/11%	6/15%	4/15%
Arc welding	10/30%	10/25%	10/30%
Spray painting/coating	3/8%	6/10%	8/15%
Processing (routing, drilling, grinding, etc.)	0/5%	2/7%	4/6%
Electronics assembly	0/3%	0/3%	0/4%
Other assembly	0/10%	0/8%	0/10%
Inspection	0/10%	0/8%	0/11%
Other	0/0%	0/0%	0/0%

Comments: (None)

G-25. My company is:

User of robots:	67%	Yes	33%	No
Manufacturer of robots:	15%	Yes	85%	No

SME/UNIVERSITY OF MICHIGAN

1984 ROBOTICS DELPHI QUESTIONNAIRE

Technology

T-I. What percent of all industrial robots purchased in the U.S. in the following years will have their controls installed as part of the robot structure, and what percent will have controls contained in a separate, independent enclosure?

	Median		
	1985	1990	1995
Controls part of structure	20%	30%	25%
Controls in separate enclosure	80%	70%	75%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Controls part of structure	10/40%	10/50%	10/50%
Controls in separate enclosure	60/90%	50/90%	50/90%

Comments:

As robots become more mobile, the need for on-board controls will increase.

Anticipate greater emphasis on standardized control system and availability of separate purchase of interchangeable control systems. Separate, independent enclosure of control systems is very important for remote robotics.

For off-line programming.

Environment prohibits too much transfer of electronics. What goes in today will become more capable and will do more work. But lion's share of work will be done by external processors.

The main reason for our preference of separate control enclosures is because we want to use a single control to monitor several robots.

Central controller.

The above assumes a very drastic reduction in size and price of controllers.

As robots get into precision assembly work, "small work" controls will become "part" of robot.

Trend is going away from Prab and Unimate controls in the robot base.

Primarily force feedback.

Depends on the industrial needs and the manufacturer's expense.

Large robots will use separate enclosure. Controls for small robots will be part of unit structure.

I see no advantage to integrating electronics into robot structure.

Assembly robots will remain separate.

As technology changes to smaller microprocessors, more controls will become self-contained in the unit.

Balance of off-line programming and safety is economics and sophistication.

T-2. What percent of all industrial robots purchased in the U.S. will include any sort of feedback-sensing device other than position and/or rate sensors?

	Median		
	1985	1990	1995
All industry	15%	35%	60%

	Interquartile Range		
	1985	1990	1995
All industry	10/20%	25/50%	40/80%

Comments:

Because of increased applications, tactile and visual sensing will increase.

Foresee greater emphasis on adaptive controls for FMS.

Mainly tactile/force sensing, some vision.

Vision will dominate but not until AI software becomes compatible with vision analysis tasks.

So far there has been, we understand, a technological lag in this area, i.e., what works in the lab is not necessarily going to work on the floor.

As robots get into precision assembly work, "small work" controls will become "part" of robot.

Lack of arc weld seam sensing at speeds exceeding 250 cm/min holding back many arc welding applications.

This is essential for the next generation of "smart" robots.

Technological breakthrough and expansion of vision and tactile sensing will propel this inclusion.

Field installations at present will become OEM with robot manufacture.

Force feedback (i.e., air pressure) and other feedback means are an advantage in specific applications and available from automated machine builders. Often considered "tooling" rather than capital equipment.

Applications for sensing devices will increase as needs increase.

Initially, majority will be smart end effectors.

As the state-of-the-art in feedback devices improves, additional robot applications will appear.

Not required in automotive applications where majority of robots are utilized. In applications such as assembly where this type of sensing is greatly needed, emphasis will still be placed on making the robot accurate and reliable.

This is a major part of robots' intelligence.

As more of the industrial robots are introduced into systems, the need for sensing by vision or otherwise will become increasingly important.

Based on assumption that by 1990 a reliable, industrial type of vision system will be available.

Tied in with "smarter" software and programming techniques.

1985: 90% photocell, 1% sonic, 2% proximity, 3% laser, 4% vision.

As robots do more delicate operations, sensors will be necessary.

Industrial robots can be reprogrammed to do new tasks, as processes change.

T-3. What percent of all industrial robots purchased in the U.S. will be incorporated into existing production facilities and processes, versus percent of robots purchased as part of a new facility?

	Median		
	1985	1990	1995
Incorporated into existing plant	80%	60%	50%
New facility	20%	40%	50%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Incorporated into existing plant	68/84%	50/75%	30/60%
New facility	16/32%	25/50%	40/70%

Comments:

Patchwork of existing production systems will continue to relieve a variety of business and economic pressures - the real revolution in productivity will occur in new facilities and production flows.

Plant replacement is slow now and will remain slow. New facility needs do exist, but the inclination to replace will continue to follow historical trends, i.e. "run them till they fall apart."

We feel it would be considerably easier to purchase robots as a part of the manufacturing cell/facility rather than incorporate them into existing facilities.

What you are asking is how many new facilities will be established. As more and more new plants are completely automated, most of them will use robots as part of the overall scheme.

This is a trade-off between saturating existing facility applications and the percent of new facility expenditures.

Retrofits will become saturated.

Only fixed capital is available for new or totally remodeled facilities. This will not change in the future.

There is greater flexibility in designing a new facility to incorporate new manufacturing systems and robotics. New products sometimes dictate new facilities. Existing facilities are renovated.

Not that many manufacturing facilities are being built.

Even though new facilities should incorporate flexible systems (i.e. robots) start-up costs and development time inhibit implementation.

I don't believe there will be a tendency to build new facilities; there will be one to modernize existing ones. The new facilities will probably be due to migration.

Too much in place to go from scratch.

Eventually our managers will understand the impact of robots and everyone will begin the transition to robots.

T-4. What percent of all industrial robots purchased in the U.S. will be table-top units, what percent floor mounted, what percent ceiling- or wall-mounted, and what percent mounted on other equipment?

	Median		
	1985	1990	1995
Table-top	20%	22%	22%
Floor	65%	57%	55%
Ceiling/wall	5%	10%	11%
Equipment	10%	11%	12%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Table-top	8/30%	10/30%	12/30%
Floor	50/80%	40/70%	38/60%
Ceiling/wall	5/10%	5/10%	5/15%
Equipment	5/10%	6/20%	10/20%

Comments:

Off floor saves space.

Mobile for flexible usage.

As applications call for more stringent tolerances, you will find users getting away from floor-mounted, articulated arm and into gantry type systems--more rigidity.

As we become more accustomed to protecting work envelopes, more radical installations will arise.

Floor-mounted includes pedestals for increasing base height.

Robots are cost-effective because of mobility due to change of process.

The percentage of table-top models should increase due to their use in electronic assembly.

Space considerations and small parts assembly.

Small assembly robots are going to be an area of intense R&D and growth. Table-top installations allow for easy incorporation into existing production lines.

Many will be interchangeable between table-top and machine.

There is no comparison between the effectiveness of floor models to table-top models.

Large floor-mounted robots dominate the market due to the automotive and general material-handling applications. However, assembly task-oriented applications will begin to rise as the confidence builds in the accuracy of the assembly type robots.

As we move more into systems, the advantages of a multi-purpose floor- or gantry-mounted robot will decrease the usage of dedicated equipment-mounted robots. The multi-purpose robots have the ability to load and unload, move pallets, change chuck jaws, change tools automatically, and do other duties with one unit.

Floor-mounted robots use valuable floor space and limit access to machines, etc. during servicing and manual back-up.

Table-top assembly.

As robots do more assembly operations, the table-top units will become more useful.

T-5. What will be the percentage distribution of robot teach/programming modes for all industrial robots purchased in the U.S.?

	Median		
	1985	1990	1995
Point-to-point	33%	22%	19%
Control pendant	50%	44%	25%
Computer programming	11%	22%	31%
Other	0%	0%	0%
Hybrid of the above	6%	11%	25%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Point-to-point	10/45%	10/40%	5/30%
Control pendant	30/65%	25/50%	10/40%
Computer programming	5/15%	10/30%	13/50%
Other	0/0%	0/0%	0/0%
Hybrid of the above	0/10%	0/25%	0//35%

Comments:

Obvious tendency will be in direction of off-line. I suspect that fine tuning with pendant will be necessary supplement; i.e., hybrid will be prevalent mode.

With artificial intelligence, units will assess problems and goals and eventually program themselves.

Still see a low-cost market for the simple pick-and-place units, with many basic applications.

As new processes are developed with robots as an integral part, the teach modes will become more computer-aided.

Improved off-line programming in hybrid with control pendant.

Future robots will be more versatile in their programmability.

A hybrid of off-line programming and control pendant should become more popular.

Flexible, integrated mode required.

An increase in specialty robots.

To be competitive in the market and able to provide a true CIM process, a robot must have a programming language to control its movement and allow communication to the outside.

Computer programming only will require the use of "smart" robots.

T-6. What will be the percentage distribution of controller types for all industrial robots purchased in the U.S. in the following years?

	Median		
	1985	1990	1995
Microcomputer	48%	53%	56%
Minicomputer	24%	29%	28%
Mainframe computer	4%	6%	6%
Programmable controller (PC)	24%	12%	10%
Other noncomputer	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Microcomputer	30/60%	30/60%	30/60%
Minicomputer	15/30%	15/38%	10/40%
Mainframe computer	0/5%	1/10%	1/10%
Programmable controller (PC)	10/28%	5/20%	5/20%
Other non-computer	0/5%	0/5%	0/5%

Comments:

As robots are integrated with other aspects of flexible ("factory") automation, we will see movement from PC through mini- to mainframe computer control.

"On Limb" VLSI control logic and intelligence!

PCs should see a stable percentage. Simple tasks require simple computers.

16- and 32-bit microcomputers with mass memory should be very popular by 1985.

This depends on whether PCs get faster.

The mainframe will probably be a high-level system downloading programs to local micros on several robots.

Many of the more sophisticated installations will include more than one controller to monitor and control the process (task).

Integrated use of robotics in manufacturing will generate more use of larger computers since total systems will be more complex. Small noncomputer controlled units will fade out.

Most controllers will be parallel micros.

Increase in controller speed and the advent of vision into robotics.

Minicomputers are relatively inexpensive and powerful. They will do bulk of future robot control.

Individual robot systems will benefit from an increase in microcomputer controller capabilities. Robotic systems will be part of a cell controlled by another micro- or minicomputer control.

As the robot technology increases so must the computing power!

Multi-tasking micros will be the wave of the future.

T-7. What percent of robots controlled by any type of computer will be programmed off-line, and what percent will be programmed on-line?

	Median		
	1985	1990	1995
OFF-line	15%	35%	50%
ON-line	85%	65%	50%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
OFF-line	10/20%	20/50%	30/70%
ON-line	80/90%	50/80%	30/70%

Comments:

Most off-line programming will require on-line touch-up until arm-mapping technology is incorporated in 1990.

No Line! Self-programming.

Off-line programming of multi-axis robots is difficult given the inability to hold part tolerance.

Integrated manufacturing will require off-line computer-controlled (-programmed) systems.

Symbolic names will be bound to physical locations on-line by moving the robot to a location and telling the system, "this is location GLERP." Algorithms will be generated off-line.

Small percentage of robots will need on-line programming.

Off-line programming still needs to overcome robot-to-robot transfer of program problems with acceptable accuracy.

Off-line defining of 3-D workplaces is a long way from the casual robot user.

Most applications are high volume requiring a minimum of control-part modification.

Off-line programming is a desirable approach, but is not widely used yet. It will start to increase as more sophisticated robot networking and software languages begin to develop.

On-line touch-up a reality in most installations.

Intelligence means off-line is easier eventually; until then we will have growing on-line programming.

T-8. Of those industrial robots purchased in the U.S. in the following years, what percent of off-line programming will be debugged, at least partially, using a CAD simulator?

	Median		
	1985	1990	1995
Off-line programming via CAD	5%	20%	40%

	Interquartile Range		
	1985	1990	1995
Off-line programming via CAD	5/10%	10/30%	20/60%

Comments:

CAD/CAM systems cost should decrease.

The drop in cost of CAD/CAM can increase the percentages.

CAD simulators are expected to lag behind introduction of extensive simulation programs.

Much time will be saved by simulation. Costs will be reduced as well.

Most firms will try it without a simulator before realizing a simulator's value.

Better and lower-cost CAD systems.

Most pick-place robots do not require simulation.

Not limited to newly purchased robots.

None but the largest companies could afford this luxury.

Simulators are a must for efficient program start-up.

Will be done as capability becomes common using vendor-provided software.

T-9. What will be the percentage distribution of production scales into which robots will be introduced in U.S. industry in the following years?

	Median		
	1985	1990	1995
Small batch	10%	17%	22%
Batch	20%	28%	33%
Mass production	70%	55%	45%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Small batch	5/15%	17/20%	15/30%
Batch	15/30%	20/35%	25/35%
Mass production	30/75%	35/67%	20/60%

Comments:

Flexible automation will overtake fixed, hard automation.

Mass production's product price is hard to beat. Small batch versatility will make some dent.

Small batch requires the combination of multiple products and disciplines which U.S. industry is still developing.

As robots get into precision assembly work, "small work" controls will become "part" of robot.

With robot costs falling, small job could be more cost-effective.

I think a robot's best use is in batch and small batch work but, based on my experiences at trade shows, most potential customers still see them as mass production devices.

Dividing line becomes "blurred" with automated batch processes.

Growth will occur in all areas.

Payback dictates mass production in order to achieve a decent rate of return on the investment dollar.

Small batch not economical to tool and program.

As we become more knowledgeable, batch is where the volume and savings potentials lie.

The use of vision along with better end effectors and automatic tool exchangers will make batch and small batch systems more viable.

Mass production is more suited for hard automation.

T-10. What will be the percentage distribution of U.S. industrial robots tied into each of the following production methods in the following years?

	Median		
	1985	1990	1995
Robotic "island" workstations	84%	67%	52%
CAD alone	0%	5%	5%
CAM alone	5%	9%	12%
CAD/CAM or CIM	11%	19%	31%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Robotic "island" workstations	70/90%	50/80%	20/65%
CAD alone	0/5%	0/5%	0/6%
CAM alone	5/10%	5/15%	5/15%
CAD/CAM or CIM	5/15%	10/30%	20/50%

Comments:

A robot with CAD is CAM.

Need for robot accuracy and need for sensors to detect malfunction will make growth slow.

T-11a. What percent of machine-tending robots purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	53%	50%	50%
5	32%	30%	30%
6	15%	20%	20%
7	0%	0%	0%
8 or more	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
No. of Axes	1985	1990	1995
4 or fewer	10/60%	25/60%	40/62%
5	20/40%	20/30%	20/35%
6	10/30%	10/30%	12/30%
7	0/5%	0/5%	0/0%
8 or more	0/0%	0/0%	0/0%

Comments:

By 1990, robots with 4 axes of motion will not be called "robots."

Mobile robots (on carts, for example) will be used in the future.

Four or fewer axes is just a manipulator.

T-11b. What percent of material transfer robots (excluding machine-tending) purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	67%	59%	60%
5	22%	29%	28%
6	11%	12%	12%
7	0%	0%	0%
8 or more	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
No. of Axes	1985	1990	1995
4 or fewer	35/80%	35/75%	30/70%
5	15/30%	15/35%	10/35%
6	5/20%	5/25%	10/25%
7	0/5%	0/0%	0/10%
8 or more	0/0%	0/0%	0/0%

Comments:

More than six axes are not required for that job.

Most transfer robots require only a few degrees of freedom.

Material handling would not need many axes.

Simple executions of duty, not much change.

T-11c. What percent of spot welding robots purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	22%	21%	14%
5	30%	29%	29%
6	45%	43%	50%
7	3%	7%	7%
8 or more	0%	01%	0%
	100%	100%	100%

	Interquartile Range		
No. of Axes	1985	1990	1995
4 or fewer	0/60%	0/50%	0/30%
5	5/30%	10/35%	10/30%
6	10/60%	15/70%	20/60%
7	0/10%	0/10%	0/15%
8 or more	0/0%	0/1%	0/5%

Comments:

Cost per axis should drop, favoring standard lines with 5 axes.

Need more dexterity for spot welding.

Spot welding (especially in auto industry) will continue to become more complex!

T-11d. What percent of arc welding robots purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	8%	6%	7%
5	39%	32%	29%
6	47%	56%	57%
7	6%	6%	7%
8 or more	0%	0%	0%
	100%	100%	100%

No. of Axes	Interquartile Range 1985	1990	1995
4 or fewer	0/30%	0/20%	0/20%
5	20/40%	20/40%	10/40%
6	20/60%	20/60%	25/65%
7	0/10%	0/15%	0/20%
8 or more	0/0%	0/1%	0/10%

Comments:

Welding is tricky. Advantages will be found for seven-axis machines. Five axes will handle the job and be most economical for all but a few jobs.

Arc welding requires more dexterity than item spot welding.

State-of-the-art arc welding, as well as spot welding, will also continue to become more complex!

T-11e. What percent of spray painting robots purchased in the U.S. will have the following numbers of axes of motion?

No. of Axes	Median 1985	1990	1995
4 or fewer	11%	9%	6%
5	28%	28%	24%
6	56%	57%	59%
7	5%	6%	11%
8 or more	0%	0%	0%
	100%	100%	100%

No. of Axes	Interquartile Range 1985	1990	1995
4 or fewer	0/50%	0/15%	0/10%
5	10/40%	10/35%	10/30%
6	20/60%	20/60%	20/70%
7	0/10%	0/15%	0/20%
8 or more	0/0%	0/0%	0/10%

Comments:

This includes rails and only servo-controlled axes.

Assuming that oscillating-type manipulators meet definition of a robot.

Don't believe that spray painting robotic technology will become more complex than it already is.

Although there will be some robots with axes above 7 and below 5, I consider their numbers to be nil.

T-11f. What percent of other processing and finishing robots purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	21%	24%	25%
5	42%	35%	31%
6	32%	35%	38%
7	5%	6%	6%
8 or more	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
No. of Axes	1985	1990	1995
4 or fewer	10/30%	10/30%	5/27%
5	25/50%	25/45%	20/46%
6	20/40%	20/50%	20/50%
7	0/10%	0/10%	0/10%
8 or more	0/0%	0/5%	0/10%

Comments:

This includes rails.

To have a dramatic effect in this area, robot vision will have to be improved.

T-11g. What percent of electronics assembly robots purchased in the U.S. will have the following numbers of axes of motion?

	Median		
No. of Axes	1985	1990	1995
4 or fewer	63%	50%	50%
5	25%	25%	25%
6	12%	25%	25%
7	0%	0%	0%
8 or more	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
No. of Axes	1985	1990	1995
4 or fewer	10/70%	10/70%	10/60%
5	15/30%	10/35%	10/30%
6	5/20%	10/30%	7/40%
7	0/5%	0/5%	0/5%
8 or more	0/0%	0/0%	0/0%

Comments:

Robotics will cause component manufacturers to conform their products to a fairly tolerant robot standard for part configuration. Robot equipment will be simplified and need fewer axes of motion.

T-11h. What percent of other assembly robots purchased in the U.S. will have the following numbers of axes of motion?

No. of Axes	Median 1985	Median 1990	Median 1995
4 or fewer	35%	32%	24%
5	35%	32%	29%
6	30%	36%	47%
7	0%	0%	0%
8 or more	0%	0%	0%
	100%	100%	100%

No. of Axes	Interquartile Range 1985	Interquartile Range 1990	Interquartile Range 1995
4 or fewer	5/50%	10/50%	5/40%
5	25/40%	25/35%	20/30%
6	10/40%	20/40%	20/50%
7	0/5%	0/5%	0/5%
8 or more	0/0%	0/0%	0/1%

Comments:

Tooling will account for some flexibility, making robots faster and more accurate with fewer motions.

The seventh axis is assumed to be a floor or overhead rail or similar device.

T-11i. What percent of inspection robots purchased in the U.S. will have the following numbers of axes of motion?

No. of Axes	Median 1985	Median 1990	Median 1995
4 or fewer	37%	24%	22%
5	25%	29%	28%
6	38%	41%	44%
7	0%	6%	6%
8 or more	0%	0%	0%
	100%	100%	100%

No. of Axes	Interquartile Range 1985	1990	1995
4 or fewer	10/50%	10/50%	1/30%
5	20/30%	20/30%	15/30%
6	10/50%	20/50%	20/60%
7	0/5%	0/10%	0/15%
8 or more	0/5%	0/5%	0/5%

Comments:

Accuracy maintenance gets tougher as the number of axes goes up. Problem won't be solved, but solution will make measuring odd shapes attractive.

T-12. What percent of all machine tools purchased in the U.S. in each of the following years will contain a robotic arm component?

	Median 1985	1990	1995
All Industry	5%	15%	25%

	Interquartile Range 1985	1990	1995
All Industry	5/10%	10/25%	20/40%

Comments: (None)

T-13. What percent of assembly systems will utilize robotic technology?

	Median 1985	1990	1995
All assembly systems	15%	30%	45%

	Interquartile Range 1985	1990	1995
All assembly systems	8/30%	20/50%	30/75%

Comments:

70% body shop.

"Hard" automation is hard to beat on a high/medium speed system.

Very high volume systems will probably not use robots.

Coca Cola bottle tops will not be assembled onto Coke bottles by robots.

T-14. What percent of programmable assembly stations purchased in the U.S. will be of the types listed below?

	Median		
	1985	1990	1995
Distributed (no tool changing)	80%	70%	70%
Centralized (all assembly operations performed at one station)	20%	30%	30%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Distributed (no tool changing)	60/85%	50/80%	40/70%
Centralized (all assembly operations performed at one station)	15/40%	20/50%	30/60%

Comments:

Cost goes down with time on simpler stations. Doing work with several stations is faster than with one. Flexible assembly suggests only one station, but cost will fall below point that warrants centralization.

I think that a lot depends on the volume. For low volume you'd use centralized, but as the volume increases you would add more robots or perhaps hand-automation.

Batch size and speed will require tool changing.

T-15. What will be the percentage distribution of coordinate systems utilized by industrial robots in the U.S.? (Definitions of each type are provided in the last page of the questionnaire.)

	Median		
	1985	1990	1995
Articulated	53%	53%	53%
Cartesian	21%	21%	21%
Cylindrical	16%	16%	16%
Spherical	10%	10%	10%
Other	0%	0%	0%
Combination of above	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Articulated	30/60%	30/60%	30/60%
Cartesian	15/25%	15/25%	15/25%
Cylindrical	5/20%	5/20%	10/20%
Spherical	5/15%	5/15%	5/15%
Other	0/0%	0/0%	0/0%
Combination of above	0/0%	0/0%	0/0%

Comments:

Software will make articulated arm easy to drive and achieve clearances around arbitrary shapes as required by unmanned stations.

Very dependent on the application.

There is a difference between the configuration of the robot and the system it can be programmed in. All good systems will allow for Cartesian programming.

Any given robot will be programmed using all of these coordinate systems.

Provided a hybrid does not change the picture.

T-16. Rank (from 1 to 13) in order of importance the percent advantages of the three different actuator types. (1 = Most important)

	Median Ranking		
	Hydraulic	Electric	Pneumatic
1. Initial cost	5	8	1
2. Maintenance cost	6	6	3
3. Load capability	1	10	6
4. Energy usage	12	11	11
5. Floor space	13	12	8
6. Use in flammable environment	11	13	2
7. Spatial Resolution[1]	9	3	13
8. Accuracy[2]	4	1	9
9. Compliance[3]	7	9	12
10. Repeatability	3	2	10
11. Speed	2	5	4
12. Mean time before failure	8	4	5
13. Ease of introduction into existing facility	10	7	7

		Interquartile Range Ranking		
		Hydraulic	Electric	Pneumatic
1.	Initial cost	4/8	5/10	1/1
2.	Maintenance cost	6/10	6/8	3/7
3.	Load capability	1/1	7/11	4/9
4.	Energy usage	7/12	8/11	5/11
5.	Floor space	8/13	7/12	5/9
6.	Use in flammable environment	3/12	10/13	2/10
7.	Spatial Resolution[1]	7/10	2/7	10/13
8.	Accuracy[2]	3/8	1/3	6/12
9.	Compliance[3]	5/10	5/11	6/12
10.	Repeatability	3/7	2/5	7/11
11.	Speed	2/7	4/8	3/8
12.	Mean time before failure	7/10	3/9	4/8
13.	Ease of introduction into existing facility	6/11	5/10	3/10

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[1] Spatial resolution is the smallest increment by which the system can divide the working space.

[2] Accuracy is a combination of the effects of: a) Spatial resolution, and b) Mechanical component inaccuracy (linkage, gears, beam deflection).

[3] Compliance is the displacement of a manipulator relative to a fixed frame in response to an external force.

Comments: (None)

T-17. What are currently the largest obstacles to the implementation of CAD/CAM- or CIM-controlled robots?

Obstacles	% of All Responses	Obstacles	% of All Responses
Cost/Economic justification	20	Exaggeration of performance	1
Interfacing with existing equipment	13	Lack of robot standards	1
Management resistance	9	Lack of suitable off-line programming	1
Corporate expertise/experience base	7	Cell versatility	1
Software limitations	5	Tools/Fixtures	1
Standard language	5	Part design	1
Accuracy	4	Speed	1
Trained engineers	4	Lack of communication standards	1
Lack of CIM or CAD/CAM systems	3	Complexity	1
Controllers	3	Lack of proven results	1
Maintenance	2	Material handling limitations	1
Reliability	2	Misuse of robot systems, giving bad impressions	1
Employee/Union relations	2	"Volume of robots/installation"	1
Changing technology	2	"Installed base is too small and dispersed"	1
Lack of suitable data base	2	"Increase in CAD usage"	1
Lack of suitable accounting practices	1	"Need for real-time simulation"	1
Lack of adaptive response	1		
Sensor limitations	1		
Applicability to current manufacturing processes	1	No obstacles exist	1

Comments: (None)

T-17a. Listed below are the most frequently cited obstacles to the current implementation of CAD/CAM- or CIM-controlled robots, as determined from the last Delphi round. How would you rank the severity of each obstacle? (1=Critical; 5=Not a limitation)

	Median Ranking
Cost/economic justification	1
Interfacing with existing equipment	2
Management resistance	3
Lack of expertise with the technology	2
Software/programming limitations	3
Maintenance	3
Labor relations	4
Machine vision limitations	3
Non-vision sensor limitations	3
Applicability to current manufacturing processes	2
Tooling/fixture limitations	3
Speed	4
Reliability	3

	Interquartile Range
Cost/economic justification	1/2
Interfacing with existing equipment	1/3
Management resistance	2/4
Lack of expertise with the technology	2/3
Software/programming limitations	2/4
Maintenance	3/5
Labor relations	3/5
Machine vision limitations	2/4
Non-vision sensor limitations	2/4
Applicability to current manufacturing processes	2/4
Tooling/fixture limitations	2/4
Speed	3/4
Reliability	2/4

Comments:

A [Interfacing with existing equipment] - especially computers. B [Cost/economic justification] and C [Management resistance] - no problem if they are the right people.

T-18. What percent of all industrial robots purchased in the U.S. will operate with two (or more) coordinated arms?

	Median		
	1985	1990	1995
All Industry	3%	10%	15%

	Interquartile Range		
	1985	1990	1995
All Industry	1/5%	5/15%	10/20%

Comments:

Loosely coordinated, i.e., not on a single controller.

However, no one will care by 1995, because only the robot units themselves will be concerned with coordinate systems.

Highly impractical. Better use one arm and dedicated fixturing.

Some strange possibilities with the development of control software and hardware (i.e., GCA's, CIMROC).

Greatly increases capability with modest increase in cost. Saves floor space.

Two arms are most often used for assembly. Currently only small percentage of robots do assembly.

Bad news. Most companies cannot cope with one arm.

T-19. What percent of robot grippers purchased in the following years will be "intelligent" (i.e., sensor-equipped with closed-loop feedback)?

	Median		
	1985	1990	1995
All Industry	5%	20%	35%

	Interquartile Range		
	1985	1990	1995
All Industry	5/10%	10/30%	25/50%

Comments:

Mainly tactile (like IBM 7565).

Benefits are phenomenal but so will be the cost.

Force and pressure feedback are valuable to avoid product damage.

Industry (robotic) will make their sensors more available.

Small batch, high speed requires that we put intelligence in grippers and fixtures to speed and simplify the robot.

Possible to avoid some feedback needs by good (clever) fixture design.

T-20. The three most frequently cited criteria for robots are arm velocity, accuracy, and repeatability. By robot type, what will be the average values for each?

	Median		
a. VELOCITY (in./sec.):	1985	1990	1995
Machine tending	40	40	50
Material transfer (excl. machine tending)	40	60	75
Spot welding	30	40	40
Arc welding	30	35	35
Spray painting/coating	40	50	50
Processing (routing, drilling, grinding, etc.)	30	30	40
Electronics assembly	40	50	55
Other assembly	35	50	60
Inspection	40	40	40

	Interquartile Range		
a. VELOCITY (in./sec.):	1985	1990	1995
Machine tending	30/40	35/60	35/100
Material transfer (excl. machine tending)	30/50	40/70	40/100
Spot welding	30/40	30/50	35/60
Arc welding	20/40	25/50	30/60
Spray painting/coating	30/40	30/50	30/60
Processing (routing, drilling, grinding, etc.)	20/30	25/40	30/40
Electronics assembly	30/40	40/60	40/80
Other assembly	30/40	30/60	30/65
Inspection	30/40	30/60	30/70

	Median		
b. ACCURACY (± in.):	1985	1990	1995
Machine tending	.01	.005	.005
Material transfer (excl. machine tending)	.02	.01	.005
Spot welding	.01	.01	.01
Arc welding	.01	.007	.004
Spray painting/coating	.05	.05	.05
Processing (routing, drilling, grinding, etc.)	.01	.005	.003
Electronics assembly	.005	.002	.001
Other assembly	.005	.004	.003
Inspection	.003	.001	.0005

	Interquartile Range		
b. ACCURACY (± in.):	1985	1990	1995
Machine tending	.01/.015	.005/.01	.005/.005
Material transfer (excl. machine tending)	.01/.05	.01/.05	.005/.05
Spot welding	.01/.02	.006/.01	.004/.01
Arc welding	.005/.02	.004/.01	.002/.01
Spray painting/coating	.02/.1	.01/.05	.01/.05
Processing (routing, drilling, grinding, etc.)	.004/.015	.002/.01	.001/.005
Electronics assembly	.002/.005	.001/.002	.001/.002
Other assembly	.004/.01	.002/.005	.001/.005
Inspection	.001/.005	.0005/.002	.0003/.001

	Median		
c. REPEATABILITY (± in.):	1985	1990	1995
Machine tending	.01	.005	.005
Material transfer (excl. machine tending)	.01	.005	.005
Spot welding	.01	.004	.002
Arc welding	.005	.004	.002
Spray painting/coating	.05	.01	.01
Processing (routing, drilling, grinding, etc.)	.005	.004	.002
Electronics assembly	.002	.001	.0005
Other assembly	.003	.002	.001
Inspection	.002	.001	.0005

	Interquartile Range		
c. REPEATABILITY (± in.):	1985	1990	1995
Machine tending	.005/.01	.003/.01	.002/.01
Material transfer (excl. machine tending)	.01/.02	.002/.01	.002/.005
Spot welding	.004/.01	.002/.01	.001/.004
Arc welding	.004/.01	.003/.005	.001/.004
Spray painting/coating	.01/.05	.008/.04	.006/.02
Processing (routing, drilling, grinding, etc.)	.001/.005	.002/.01	.001/.005
Electronics assembly	.001/.004	.0005/.002	.0005/.001
Other assembly	.002/.005	.002/.004	.001/.004
Inspection	.001/.004	.0005/.002	.0005/.001

Comments:

Accuracy will become increasingly important as CAD/CAM begins to generate robot programs - the robot will then have to go to a position commanded from a remote source.

Accuracy will improve with arm mapping and compensation in the control for individual robot arms.

Accuracy is already good enough. Compliance and smarts to use robot correctly is needed.

Part B & C of this question are dependent on number of axes and type (pedestal or gantry) of robot.

Values given are for medium-sized robots - small robots will be in the ±.0002 range.

Accuracy and repeatability must happen or in fact be better than stated for robots to become generally acceptable to industry.

Velocity - most are adequate.
Accuracy - should be within thousandths of an inch.
Repeatability - should also be within thousandths of an inch.

Accuracy and repeatability will increase in a normal evolutionary manner, but because of requirements of CIM sensor systems, especially vision, will partly compensate the need for these requirements.

Accuracy will naturally get better, not due to necessity, but for saleability.

T-21. By robot type, what percent of all industrial robots purchased in the U.S. will include a machine vision capability of any sort in the following years?

	Median		
	1985	1990	1995
Machine tending	5%	10%	15%
Material transfer (excl. machine tending)	5%	10%	15%
Spot welding	3%	5%	10%
Arc welding	5%	20%	30%
Spray painting/coating	2%	5%	10%
Processing (routing, drilling, grinding, etc.)	5%	10%	15%
Electronics assembly	10%	30%	45%
Other assembly	10%	20%	35%
Inspection	20%	40%	60%

	Interquartile Range		
	1985	1990	1995
Machine tending	1/5%	5/15%	5/25%
Material transfer (excl. machine tending)	2/5%	5/20%	10/30%
Spot welding	1/5%	3/15%	3/20%
Arc welding	5/10%	10/35%	15/60%
Spray painting/coating	0/5%	2/12%	5/15%
Processing (routing, drilling, grinding, etc.)	2/5%	7/20%	10/30%
Electronics assembly	5/20%	15/40%	20/70%
Other assembly	5/15%	10/40%	20/50%
Inspection	10/20%	25/50%	40/75%

Comments:

Major use will be second and third offsets for unfixtured parts.

Inspection needs vision for speed. Accuracy, however, may never be enough.

Parts will be designed and other sensors provided which will reduce need for vision.

Hybrid robots may combine or change some of these columns.

T-22. Of those vision-equipped robots installed in the years listed below, what percent of the vision systems will be supplied by the following sources?

	Median		
	1985	1990	1995
Robot manufacturers	22%	32%	48%
Vision systems manufacturers	66%	52%	39%
Independent supplier houses	6%	11%	8%
User-developed	6%	5%	5%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Robot manufacturers	10/30%	20/40%	25/60%
Vision systems manufacturers	40/80%	35/61%	25/50%
Independent supplier houses	4/10%	5/18%	5/15%
User-developed	0/10%	0/10%	0/10%
Other	0/0%	0/0%	0/0%

Comments:

Supplied and integrated into the robot by the robot company. Software designed by the robot company. Camera manufactured elsewhere.

The vision manufacturers will be contracted by the robot manufacturers for the vision package. As a result, the robot manufacturers will be a supplier of a complete system.

Technology will develop to a modular add-on.

As vendors improve vision systems there will be less need for user-developed systems.

Systems installed by robot manufacturers will continue to be no. 1 as far as reliability is concerned.

As engineers become smarter, they will be more self-sufficient.

Supplier will bring systems together.

T-23. What percent of all industrial robots (by RIA definition) purchased in the following countries from all sources will include a machine vision capability of any sort in the following years?

	Median		
	1985	1990	1995
Western Europe	10%	20%	40%
Japan	15%	35%	20%
Canada	8%	20%	38%

	Interquartile Range		
	1985	1990	1995
Western Europe	5/20%	10/40%	20/60%
Japan	8/40%	15/60%	30/80%
Canada	3/15%	6/30%	15/40%

Comments:

Japanese will find less technology to accomplish the required tasks.

Japanese need AI to really make vision an autonomous capability. Now they depend heavily on the user's understanding their system for its use. Japanese equipment is hard to understand, or their descriptions are, at least.

T-24. What percent of all industrial robots purchased in the U.S. will include "scene analysis" for feedback to the robot to enable it to select a part from a bin of mixed parts?

	Median		
	1985	1990	1995
All Industry	2%	10%	18%

	Interquartile Range		
	1985	1990	1995
All Industry	1/5%	5/15%	10/30%

Comments: (None)

T-25. What percent of arc welding robots purchased in the U.S. will incorporate a seam tracking mechanism?

	Median		
	1985	1990	1995
All Industry	15%	35%	55%

	Interquartile Range		
	1985	1990	1995
All Industry	10/25%	20/50%	30/75%

Comments:
Expect rapid growth in seam trackers.

Arc welding dictates seam tracking due to arc error.

T-26. What will be the three most active areas of robotics or robotics-related research and development (in terms of funding) over the course of the next five to seven years?

Responses	% of All Responses
Sensors - general	6%
Vision	21
Tactile sensors	4
Weld seam tracking	6
Controllers/software	14
Programming	7
Intelligence/AI	7
Integration into systems/CAD-CAM	13
Increased accuracy	5
Increased capacity	2
Gripper design/pact presentation	3
Arm structure	2
Design for assembly	3
Modularity	2
Mobility	2
"Basic mechanisms"	1
Military applications	1
Cost reduction	1
	100%

Comments: (None)

T-27. By robot type, what percent of all industrial robots purchased in the U.S. in the following years will include a touch- or force- (i.e., contact-) sensing device with feedback?

	Median		
Industry	1985	1990	1995
Machine tending	5%	15%	25%
Material transfer (excl. machine tending)	5%	15%	30%
Spot welding	5%	5%	10%
Arc welding	5%	10%	10%
Spray painting	0%	0%	0%
Processing (routing, drilling, grinding, etc.)	5%	20%	40%
Electronics assembly	10%	20%	40%
Other assembly	10%	25%	40%
Inspection	5%	15%	20%

	Interquartile Range		
Industry	1985	1990	1995
Machine tending	3/10%	10/20%	15/50%
Material transfer (excl. machine tending)	5/10%	10/30%	20/50%
Spot welding	0/10%	5/15%	5/20%
Arc welding	0/10%	2/15%	5/20%
Spray painting	0/5%	0/5%	0/10%
Processing (routing, drilling, grinding, etc.)	5/10%	15/30%	30/60%
Electronics assembly	5/25%	15/50%	25/80%
Other assembly	5/15%	15/30%	30/50%
Inspection	2/20%	4/50%	10/60%

Comments:

To be used mostly in the assembly and inspection processes.

Tactile feedback will diminish as vision improves.

T-28. Of those robots equipped with touch or force sensors, installed in the years listed below, what percent of these sensory systems will be supplied by the following sources?

	Median		
	1985	1990	1995
Robot manufacturers	35%	56%	63%
Contact sensors systems manufacturers	35%	28%	21%
Independent supplier houses	18%	11%	11%
User-developed	12%	5%	5%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Robot manufacturers	15/50%	30/60%	45/70%
Contact sensors systems manufacturers	10/50%	10/40%	10/30%
Independent supplier houses	5/25%	5/25%	5/25%
User-developed	5/15%	0/15%	0/10%
Other	0/0%	0/0%	0/0%

Comments:

Integrated into the robot and supplied to the customer by the robot company.

Software developed by the robot company. Sensor materials manufacturered elsewhere.

Sensing response has to be programmed and will be more than just a change in overall robot course of action. A single axis will have to be programmed (e.g., to tighten grip) and that will take better software than we now have to allow multi-company cooperation.

T-29. What percent of all industrial robots (by RIA definition) purchased in the following countries from all sources will include a touch- or force-sensing device with feedback?

	Median		
	1985	1990	1995
Western Europe	10%	20%	25%
Japan	20%	30%	35%
Canada	10%	20%	30%

	Interquartile Range		
	1985	1990	1995
Western Europe	5/20%	15/40%	20/50%
Japan	10/30%	20/50%	25/60%
Canada	3/15%	12/30%	20/40%

Comments:

This sort of research and product is something the Japanese can package and sell. Unless the Japanese find something better in sensing, they will go for this.

Touch sensors can be very simple, and virtually any robot programming approach can branch on binary condition. Any application which would benefit from a touch sensor will have a touch sensor.

T-30. By robot type, what percent of all industrial robots purchased in the U.S. in the following years will include any sort of non-contact, non-vision sensing devices (e.g., proximity and/or range detectors, temperature detectors, etc.)?

	Median		
Industry	1985	1990	1995
Machine tending	5%	15%	20%
Material transfer (excl. machine tending)	10%	20%	30%
Spot welding	5%	10%	10%
Arc welding	5%	15%	30%
Spray painting	3%	5%	10%
Processing (routing, drilling, grinding, etc.)	5%	15%	20%
Electronics assembly	5%	20%	35%
Other assembly	10%	20%	30%
Inspection	10%	30%	40%

	Interquartile Range		
Industry	1985	1990	1995
Machine tending	3/10%	5/20%	10/40%
Material transfer (excl. machine tending)	5/10%	10/25%	20/40%
Spot welding	0/5%	0/20%	0/30%
Arc welding	3/10%	4/30%	8/50%
Spray painting	0/5%	5/15%	8/20%
Processing (routing, drilling, grinding, etc.)	5/10%	5/30%	10/40%
Electronics assembly	3/15%	5/30%	5/50%
Other assembly	5/20%	15/30%	15/50%
Inspection	5/20%	10/30%	15/50%

Comments:

Eddy current, surface-to-gun sensing would be safe and would make the process more consistent.

I don't know of many robot manufacturers that supply any type of sensors inherent to the robot, except to monitor internal workings for diagnostic purposes.

Proximity sensors should be used widely for safety. They also can protect delicate parts.

T-31. For all industrial robots possessing non-contact, non-vision sensors purchased in the U.S. in the following years, what will be the percentage distribution among sensor types listed below?

	Median		
	1985	1990	1995
Proximity detectors	67%	65%	61%
Range detectors	28%	29%	28%
Temperature detectors	5%	6%	11%
Other	0%	0%	0%
Combination of above	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Proximity detectors	40/75%	40/75%	25/65%
Range detectors	15/30%	15/35%	10/35%
Temperature detectors	1/10%	5/10%	5/15%
Other	0/0%	0/0%	0/0%
Combination of above	0/0%	0/0%	0/0%

Comments:

Vision and infared systems will take the market from these systems because they should do the same job and give better information.

This is dependent on application. I think, for the most part, this type of sensor will be used for collision avoidance/safety except for machine tending, where proximity or a combination of sensors is now being used.

I think that people who need them will add them.

I believe more sensors will be range finding or proximity types.

Temperature might be helpful for foundry work.

T-32. Of those robots equipped with non-contact, non-vision sensors installed in the years listed below, what percent of these sensory systems will be supplied by the following sources?

	Median		
	1985	1990	1995
Robot manufacturers	35%	39%	44%
Non-contact sensor systems manufacturers	24%	28%	23%
Independent supplier houses	24%	22%	22%
User-developed	17%	11%	11%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Robot manufacturers	10/50%	15/50%	20/60%
Non-contact sensor systems manufacturers	10/30%	10/40%	10/50%
Independent supplier houses	10/30%	10/30%	5/35%
User-developed	2/30%	2/20%	5/15%
Other	0/0%	0/0%	0/0%

Comments:

User performs the integrations, usually.

T-33. What percent of all industrial robots purchased in the following countries will include any sort of non-contact, non-vision sensors?

	Median		
	1985	1990	1995
Western Europe	10%	20%	30%
Japan	20%	40%	40%
Canada	8%	20%	30%

	Interquartile Range		
	1985	1990	1995
Western Europe	5/30%	10/40%	15/70%
Japan	6/40%	12/60%	15/80%
Canada	5/15%	10/30%	15/45%

Comments: (None)

T-34. What percent of all industrial robots purchased in the U.S. will achieve their required operational accuracy by sensors and transducers within the robot, and what percent will achieve it by external, hard-tool guidance?

	Median		
	1985	1990	1995
Internal sensors	33%	47%	60%
External sensors	56%	42%	30%
Both necessary	11%	11%	10%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Internal sensors	10/40%	30/50%	40/70%
External sensors	30/75%	30/60%	20/40%
Both necessary	0/20%	5/20%	0/20%

Comments:

As internal sensors get better, more numerous, cheaper, and cheaper to use, external guides will become less necessary.

T-35. What percent of all industrial robots purchased in the U.S. will possess some degree of self-propulsion (i.e., the capability of moving from one work site to another, even if this distance is small)?

	Median		
	1985	1990	1995
Movement along a track	5%	15%	21%
Unlimited mobility	0%	5%	8%
No mobility	95%	80%	71%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Movement along a track	5/10%	10/20%	15/30%
Unlimited mobility	0/2%	1/5%	4/10%
No mobility	89/95%	70/85%	55/79%

Comments:

Unlimited mobility still seems a long way off.

T-36. What is the probability of having a standardized off-line programming language for the systems listed below by the end of the following years?

	Median		
	1985	1990	1995
Robots	0%	10%	25%
Machine vision	0%	10%	25%

	Interquartile Range		
	1985	1990	1995
Robots	0/5%	3/30%	10/60%
Machine vision	0/4%	2/30%	8/50%

Comments:

This is one of the biggest mistakes made by RIA and SME: Focus attention on "Programming Standards." Look at the turmoil and chaos in the computer industry. Look at the government's selection of first "Jovial" and then "ADA."

Programming standards establishment is simple: the manufacturer of the biggest, most sophisticated, and most sold will be the standard!

This is ambiguous; "industry-wide" depends on vendors; GE or Westinghouse could do it themselves.

With the parties in the game, no serious standardization taking place.

Production levels are so low (compared to other industrial applications) that product differentiation becomes the selling point.

A standardized language is not necessarily a good thing. No one language could do all things well anymore than one kind of automobile could satisfy everyone's transportation requirements.

What is more important are interface standards between subsystems. Also possible is a standard superstructure composed of hierarchical control levels.

This is very important and it is possible, but don't see it happening.

Standardizing anything with vendors takes a long time to develop.

Having a standardized language (e.g., APT) available, and having that language widely used are two very different things.

Unless drastic steps are taken by E.I.A. or other institutions, each manufacturer will develop its own software.

The cruel world of the marketplace will tell.

T-37. What is the probability of having a standardized on-line programming language for the systems listed below by the end of the following years?

	Median		
	1985	1990	1995
Robots	0%	10%	20%
Machine vision	0%	10%	15%

	Interquartile Range		
	1985	1990	1995
Robots	0/5%	5/20%	10/50%
Machine vision	0/5%	1/15%	5/50%

Comments:

On-line programming will have a very low priority.

Only if users insist on standardization.

Vendors will fight for market share with different products.

T-38. My company is:	User of robots:	Yes: 84%	No: 16%
	Manufacturer of robots	Yes: 5%	No: 95%

S.M.E./UNIVERSITY OF MICHIGAN
1984 ROBOTICS DELPHI QUESTIONNAIRE
Sociological

S-1. How many robots of all types do you foresee as being in operation in the U.S. for each of the following years?

	Median		
	1985	1990	1995
Total robots:	14,000	40,000	90,000

	Interquartile Range		
	1985	1990	1995
Total robots:	10,0000/15,000	30,000/60,000	60,000/120,000

Comments:

Depends on economics (capital vs. labor) and the state of the economy.

Usage to grow exponentially.

Less than original predictions - unless economy picks up more than expected.

The "robotics explosion" has been an outcome of a good public relations effort.

Assumes improved economic conditions and satisfactory solutions to training displacement/continued employment issues; lack of either will slow the implementation of robots significantly.

Applications do not come as easily as anticipated.

S-2. Given the current labor content of production, forecast the actual percentage of workers that will be displaced in the U.S., by occupation.

(Please note: Displacement does not necessarily mean disemployment, but merely those existing jobs taken over by robots. Displaced workers may be transferred, quit, enter early retirement, etc., as well as be disemployed.)

	Median		
	Percent Displacement		
Occupation:	1985	1990	1995
Assemblers	2%	5%	10%
Inspectors	1%	3%	6%
Packers (excl. meat and produce)	1%	2%	5%
Production painters	5%	10%	20%
Welders and flamecutters	5%	10%	20%
Machinists and machine operators	3%	10%	13%
Tool and die makers	0%	1%	2%
Metalcraft workers	1%	3%	6%
Construction crafts (incl. carpenters, electricians, plumbers)	0%	0%	1%
Textile workers	1%	2%	5%
Mining workers	0%	2%	4%
Agricultural workers	0%	1%	2%

	Interquartile Range		
	Percent Displacement		
Occupation:	1985	1990	1995
Assemblers	1/3%	3/10%	5/15%
Inspectors	.1/2%	1/5%	3/10%
Packers (excl. meat & produce)	.3/1%	1/6%	3/14%
Production painters	3/5%	9/15%	15/25%
Welders and flamecutters	2/5%	5/15%	12/25%
Machinists and machine operators	2/5%	5/10%	10/15%
Tool and die makers	0/1%	1/5%	1/7%
Metalcraft workers	1/3%	2/5%	3/8%
Construction crafts (incl. carpenters, electricians, plumbers)	0/0%	0/1%	0/3%
Textile workers	0/2%	1/5%	2/25%
Mining workers	0/1%	1/5%	2/10%
Agricultural workers	0/.1%	0/2%	1/5%

Comments:

Actual displacement in the same occupation may vary considerably across industries.

All estimates reflect a change in 1980 employment base.

Answers are with respect to robots only; FMS's will displace many more.

I'm not sure if any tool and die makers will be displaced because they are usually involved in custom type work--additionally, in my opinion, they manufacture small quantities of tool/dies. It is quite possible that the growth in the use of robots will place new demands for tool/die makers, for end-of-arm tooling, etc.

Many of the above positions will be eliminated by other forms of automation and technology. (Optical recognition, real time gaging, etc.)

This displacement will occur if productivity per worker improves without a proportionate increase in revenues. Textiles will go overseas to protect the bottom line.

Percentages are relative to current employment level.

The actual percent will depend upon the effort expended to utilize robots. There is a potential for 50% or more of most manufacturing operations could be replaced with a robot.

The easier applications have been done and in other areas hard automation will be more appropriate than robots.

There will be relatively little robotic penetration that will result in job displacement by 1985. Penetration will be significant by 1990 and begin accelerating by 1995, by which time manufacturers will have realized that they must aggressively automate or risk a major loss of market share.

These answers are for robots only, which will be a relatively minor factor in causing labor displacement.

S-3. Relative to the previous question, what do you forecast will be percentage of workers actually displaced (see note in S-2) in the U.S. as a result of the installation of robots, by industry?

	Median		
	Percent Displacement		
Industry	1985	1990	1995
All industry average	2%	4%	8%
Agriculture	0%	0%	1%
Mining and extractive	.5%	2%	4%
Construction	0%	0%	1%
Electricity generation	0%	0%	1%
Consumer non-durables	2%	4%	10%
Non-metal primary commodities	1%	4%	7%
Primary metals	.5%	4%	10%
Non-metal fabricated commodities	1%	3%	6%
Fabricated metal products	2%	5%	8%
Machinery manufacture	1%	3%	6%
Electronics and precision equipment	3%	10%	15%
Automotive	5%	10%	18%
Aerospace	2%	5%	9%
Other transportation equipment	2%	3%	8%

	Interquartile Range		
	Percent Displacement		
Industry	1985	1990	1995
All industry, average	1/4%	2/6%	4/15%
Agriculture	0/.1%	0/1%	0/5%
Mining and extractive	0/2%	0/4%	1/10%
Construction	0/0%	0/1%	0/2%
Electricity generation	0/0%	0/0%	0/1%
Consumer non-durables	0/2%	1/5%	3/12%
Non-metal primary commodities	0/2%	2/5%	3/10%
Primary metals	0/2%	1/5%	3/10%
Fabricated metal products	.5/2%	3/6%	6/15%
Machinery manufacture	1/2%	2/5%	5/10%
Electronics and precision equipment	1/5%	3/12%	6/18%
Automotive	4/5%	6/15%	15/23%
Aerospace	.6/3%	2/8%	3/15%
Other transportation equipment	0/3%	1/6%	2/12%

Comments:

The percentage by industry will depend heavily upon the number of middle-aged workers displaced (more than youth not allowed in or early retired older workers); plus the political strength of that industry's labor unions and state-by-state economic effects.

In the transition to automation, many workers displaced during the downside of the business cycle will simply not be recalled when production improves.

The key word again is 'robots' vs. other forms of automation.

Labor will be most affected by a change of product designs and by a shift in industry types more than by direct competition from robots.

S-4. Aside from the direct effects of the installation of robots upon production workers, what do you forecast will be the actual percentage decrease (-) or increase (+) of non-production personnel?

	Median Percent of Actual Change (+/-)		
	1985	1990	1995
Upper administrative and managerial	0%	0%	0%
Secretarial and clerical	0%	0%	0%
Engineering and computer programming	1%	3%	6%
Line supervisory	-1%	-2%	-3%
Machine maintenance	2%	3%	7%
Building maintenance	0%	0%	0%
Medical and other service staff	0%	0%	0%

	Interquartile Range Percent of Actual Change (+/-)		
	1985	1990	1995
Upper administrative and managerial	0/0%	0/0%	0/0%
Secretarial and clerical	-1/0%	-3/0%	-5/0%
Engineering and computer programming	.5/5%	2/8%	5/12%
Line supervisory	-1/0%	-3/-1%	-5/-1%
Machine maintenance	0/2%	1/5%	1/10%
Building maintenance	0/0%	0/0%	0/0%
Medical and other service staff	0/0%	-1/0%	-1/0%

Comments:

A decrease in labor-intensive replaced by an increase in robotic/automation, i.e., intelligent-machine-intensive will result in a) less need for most human labor, and b) a general increase in the quality of labor and service (i.e. non-production personnel) to that labor.

Service industries and specialized services will continue to grow. Therefore, there will be greater numbers of companies and consequently more people in given levels of work.

New forms of factory automation should require less maintenance than previous mechanical machines.

S-5. What do you forecast will be the industry-wide percentage of workers actually displaced as a result of the installation of robots abroad?

	Median		
	1985	1990	1995
Western Europe*	1%	4%	8%
Japan	3%	7%	10%
Canada	1%	2%	6%

*includes Scandinavia

	Interquartile Range		
	1985	1990	1995
Western Europe*	0/2%	1/5%	3/10%
Japan	1/5%	2/8%	4/12%
Canada	0/1%	2/4%	3/8%

*includes Scandinavia

Comments:

Japan will lead the way into robotic manufacturing, and fifth- and sixth-generation computer intelligence systems. Her workers will shift into information management production much as Switzerland did into money exchange and banking.

Robots alone not a big dislocator.

Western Europe's and Canada's government labor policy will initiate economic impact of technology.

There are many institutional constraints in Europe to mitigate the pace of worker displacement by robots.

S-6. When robots become implemented in typical American factories at significant levels, what will be the average effect (percent change) on the total number of production man-hours required in each of the following industries?

Median

Percent Change in Man-Hour Requirements (±)

	1985	1990	1995
Agriculture	0%	0%	0%
Mining and extractive	0%	-1.5	-2%
Construction	0%	0%	0%
Electricity generation	0%	0%	0%
Consumer non-durables	-1%	-3%	-5%
Non-metal primary commodities	0%	0%	0%
Primary metals	0%	-5%	-10%
Non-metal fabrication	-1%	0%	3%
Fabricated metal products	-1%	-5%	-10%
Machinery	-2%	-5%	-7%
Electronics	0%	-4%	-8%
Automotive	-5%	-10%	-15%
Aerospace	0%	-1%	-6%
Other transportation equipment	-1%	-3%	-7%

Interquartile Range

Percent Change in Man-Hour Requirements (±)

	1985	1990	1995
Agriculture	-1/0%	-5/0%	-10/1%
Mining and extractive	-1/0%	-20/0%	-30/0%
Construction	-1/0%	-5/0%	-5/1%
Electricity generation	0/2%	0/5%	0/20%
Consumer non-durables	-10/0%	-10/4%	-15/6%
Non-metal primary commodities	0/5%	-5/5%	-10/5%
Primary metals	-5/2%	-15/4%	-20/0%
Non-metal fabrication	-1/3%	-5/10%	-10/15%
Fabricated metal products	-5/2%	-15/-1%	-40/-2%
Machinery	-5/-2%	-10/-1%	-15/-2%
Electronics	-3/2%	-5/8%	-10/10%
Automotive	-5/.2%	-10/.5%	-18/1%
Aerospace	-2/1%	-4/2	-10/4%
Other transportation equipment	-3/0%	-6/-1%	-9/-2%

Comments:

Consumer non-durables will shift into tailor-made, and then personally-designed one-of-a-kind with increased personal servicing, and less human labor on the actual production. I.e., more labor-intensive choosing and designing for each customer; however, once a decision has been made, AI/robot machine production from general material stock.

E.g., 1990: 15,000 auto robots displace 30,000 hourly workers = 5% of 600,000 current work force.

Robots will not be the major factor.

S-7a. By what year, if ever, will the average production worker's work week fall to 35 hours or below?

Year: 1992/1995/1995 or Never: 29% of all responses

Comments:

Demographics work against this happening within the next 15-20 years.

Depends on wages compensation.

This depends on how competitive U.S. becomes in the world economy.

S-7b. By what year, if at all, will the average production worker's work week fall to 32 hours or below?

Year: 1995/2000/2010 or Never: 46% of all responses

Comments:

Human factors research is needed to discover how many hours/day a week.

Assume personnel remains constant, hours will decrease to equal to or less than 32 by 1992; if displacement is high, hours for remaining workers may never drop. This is a critical issue.

Demographics will play an important role. If aging of labor force continues, this may result in increased use of "part-time" elderly workers, thereby lowering the average work week.

Depends more on union activity than direct effects of robots.

Depends on economic recovery (i.e., incentive for resource and development, investments and savings).

Not because of robots.

Only for some industries.

There will be fewer workers, but work week will remain above 32 hours.

This will be a combined effect of the reduced manpower due to the effects of the automation and the increased maintenance requirements.

It is going to happen. We can't expand the world economy enough to employ the entire potential work force 40 hours/week. Germany almost went to 36 hours during the spring of 1984 in the machinist trades.

S-8. What will be the percentage breakdown of sources of future robotic technical personnel?

	Median		
	1985	1990	1995
Graduates of specialized technical school or junior college programs	12%	17%	28%
Graduating college students	12%	22%	22%
Retrained in-house personnel	59%	44%	33%
Experienced personnel from other manufacturers	12%	11%	11%
Experienced personnel from robot vendors	5%	6%	6%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Graduates of specialized technical school or junior college programs	5/15%	10/20%	15/30%
Graduating college students	8/20%	10/25%	15/30%
Retrained in-house personnel	50/67%	40/50%	30/40%
Experienced personnel from other manufacturers	7/15%	10/12%	8/15%
Experienced personnel from robot vendors	2/7%	3/10%	4/10%
Other	0/0%	0/5%	0/0%

Comments:

In-house people will evolve into the robotics gurus of the future.

We will run out of such [in-house] people to retrain. "Universities and institutions" are not generally "sources of funding." They certainly can be sources of trained personnel but generally someone else pays the tab.

S-9a. What will be the sources of funding for the training of new, upcoming robotics personnel to handle installation, maintenance and oversight functions?

	Median		
	1985	1990	1995
Federal government	6%	6%	8%
State and local governments	6%	9%	9%
Private industry	76%	66%	60%
Unions	0%	0%	0%
Universities and institutions	6%	6%	8%
Trainees themselves	6%	13%	15%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Federal government	2/10%	5/10%	5/10%
State and local governments	5/6%	5/10%	5/10%
Private industry	40/80%	40/80%	35/80%
Unions	0/2%	0/5%	0/5%
Universities and institutions	5/10%	5/10%	5/15%
Trainees themselves	3/15%	5/15%	5/15%
Other	0/0%	0/0%	0/0%

Comments:

There is a pattern similar to that for the early computer industry, where the main early sources of training were vendors and user firms, with universities becoming more important as time passed.

Some private industry may be pursued jointly with unions.

The biggest impact on the unions will be in the 1985-1990 time frame. Therefore, they will expend funds on retraining programs during that period.

"Universities and institutions" assumes that some and possibly many community-technical college-high schools may become owned by private industry.

Universities/institutions are really suppliers, funded by public monies and private industry.

If industry sees the ROI, there will be no shortage of funding internally.

Universities, unless they have technology programs (as opposed to engineering programs), will train very few if any personnel for these jobs. However, other institutions, e.g., community colleges, will take on an increasing share as time goes by. In future rounds, universities should be put in a separate category from technical schools and community colleges; that is, separate training functions from educational functions.

Private Industry; the users of robots will awaken to the fact that the technology of robotics is only going to be used if the people installing, maintaining, and overseeing its use are COMPETENT. Technology without people who can understand and apply it is worthless and a waste of capital. Waiting for others to provide it will be too costly.

S-9b. What will be the sources of funding for the training of new, upcoming robotics personnel to handle programming and operational duties?

	Median		
	1985	1990	1995
Federal government	6%	6%	6%
State and local governments	6%	6%	6%
Private industry	70%	70%	71%
Unions	0%	0%	0%
Universities and institutions	6%	6%	6%
Trainees themselves	12%	12%	11%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Federal government	0/10%	0/10%	0/10%
State and local governments	2/10%	5/10%	0/10%
Private industry	50/80%	40/80%	45/75%
Unions	0/0%	0/2%	0/0%
Universities and institutions	0/10%	0/10%	0/12%
Trainees themselves	0/15%	0/15%	0/18%
Other	0/0%	0/0%	0/0%

Comments:

There is a pattern similar to that for the early computer industry, where the main early sources of training were vendors and user firms, with universities becoming more important as time passed.

This will be a career direction for prospective employees--heavily for the trainees themselves.

During the 1985-1990 time frame, unions will expend funds on retraining programs.

Unions will negotiate contracts for private industry or government to pay for the training. Universities sell the training and therefore will not turn it except as it brings in additional R&D monies or is a gift to the institution for specific scholarships in robotics.

1) Universities/institutions are really suppliers, funded by public monies and private industry. 2) Unions will have somewhat less motivation to support/influence this than installation, maintenance programs.

S-10. What will be the sources of funding for the retraining of displaced personnel to handle installation, maintenance, and oversight functions?

	Median		
	1985	1990	1995
Federal government	11%	11%	12%
State and local governments	11%	11%	12%
Private industry	68%	68%	68%
Unions	4%	3%	1%
Universities and institutions	0%	0%	0%
Trainees themselves	6%	7%	7%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Federal government	10/12%	10/15%	10/15%
State and local governments	5/15%	8/15%	5/15%
Private industry	55/73%	50/75%	45/80%
Unions	0/5%	0/8%	0/10%
Universities and institutions	0/5%	0/5%	0/5%
Trainees themselves	4/7%	0/10%	0/10%
Other	0/0%	0/0%	0/0%

Comments:

Unions will negotiate contracts for private industry or government to pay for the training. Universities sell the training and therefore will not fund it except as it brings in additional R&D monies or is a gift to the institution for specific scholarships in robotics.

Heavily private industry.

We know unions are already including retraining provisions in their contracts to protect job security - Ford 5¢/hr; at GM 10¢/hr; IAM; Communication Workers of America.

The numbers displaced will start to fall off in the early to mid-1990's as everyone understands the new reality. Older workers will be leaving the work force and the newer ones will have more education. Also industry will hire more selectively.

Unions will have somewhat greater motivation to support/influence retraining programs than new-hire programs.

S-11. As a result of the introduction of robotic equipment purchased in the years listed below, what will be the average retraining period required (in days) for the acquisition of the following robot-related skills?

	Median		
	1985	1990	1995
Maintenance	30	30	25
Production scheduling	5	10	7
Equipment operation	10	10	10
Programming	10	15	10
Line supervisory	5	7	5

	Interquartile Range		
	1985	1990	1995
Maintenance	10/45	15/50	20/50
Production scheduling	5/21	5/15	5/15
Equipment operation	5/10	5/15	5/10
Programming	10/30	10/25	10/30
Line supervisory	5/14	5/10	5/10

Comments:

This depends heavily upon who does the training if industry pays for it and does the training days. If it is third-party-paid and academic institutions do the training, then semesters, even years.

As robots progress, the machinery within them will get more complex for maintenance people but easier to use for the user and program people.

Depends on present skills of workers when robotic equipment is installed, e.g., a skilled MX worker may require little retraining for robotic equipment MX.

The training time requirement may increase over the span of years because of increased technological complexities, or it may decrease in the way that "user-friendly" computer programs have diminished many computer process training periods.

System complexity will increase over time, resulting in more comprehensive training.

The training required must be sufficient to deal with the basic technologies of electronics, computers, and fluid power.

Some of these numbers may be high if the systems are extremely user-friendly; they may be low if technological complexity is greatly increased.

Training should stay constant or decrease as training tools become more sophisticated.

S-12a. It has been argued that, with the recent flurry of new robotics training programs at colleges, universities, and other institutions, there will be a surplus of trained workers by the latter part of the decade. For each of the following categories, do you agree?

	Median
Installation, maintenance, etc.	NO
Programming, operation, etc.	NO

	Interquartile Range
Installation, maintenance, etc.	Yes/No
Programming, operation, etc.	Yes/No

Comments:

While this training is good, it is the application of this knowledge that will determine who is really trained to handle the total systems approach that is required for successful robotic installations.

Engineering talent may be in short supply, but the technicians and lower tasks listed above will not likely be a problem.

I am not sure that we really have very many training programs on line now; I also suspect that what we need are seasoned manufacturing people with computer and robotics skills to achieve robotics installations.

S-12b. Out of every 10 newly-trained potential robotics workers, how many will find employment in the U.S. robotics field in each category?

	Median		
	1985	1990	1995
Installation, maintenance, etc.	10	10	10
Programming, operation, etc.	10	10	10

	Interquartile Range		
	1985	1990	1995
Installation, maintenance, etc.	10/10	9/10	8/10
Programming, operation, etc.	10/10	10/10	10/10

Comments:

The real training is occurring for engineers and technicians, especially the latter.

S-13a. How will production workers undergoing displacement (see definition in question S-2) be affected?

	Median Percent of Workers Affected		
	1985	1990	1995
Transferred within plant, no retraining	51%	39%	33%
Transferred within plant, with retraining	31%	39%	44%
Transferred to another plant, no retraining	5%	6%	6%
Transferred to another plant, with retraining	3%	6%	6%
Early retirement	5%	5%	5%
Voluntary termination (quitting)	4%	4%	4%
Involuntary termination (fired)	1%	1%	2%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Workers Affected		
	1985	1990	1995
Transferred within plant, no retraining	20/55%	20/45%	10/40%
Transferred within plant, with retraining	20/37%	20/40%	25/50%
Transferred to another plant, no retraining	1/5%	1/6%	1/6%
Transferred to another plant, with retraining	0/5%	0/6%	0/8%
Early retirement	5/5%	4/10%	5/6%
Voluntary termination (quitting)	1/5%	1/5%	1/5%
Involuntary termination (fired)	0/5%	0/10%	0/5%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-13b. Of those workers transferred, either in-plant or to a sister plant, what percent will be promotions, what percent demotions, and what percent strictly lateral movements?

	Median		
	1985	1990	1995
Promotions	5%	10%	10%
Demotions	11%	10%	10%
Lateral transfers	84%	80%	80%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Promotions	5/15%	5/20%	5/20%
Demotions	5/12%	5/15%	5/10%
Lateral transfers	70/90%	75/85%	80/85%

Comments:

Depends on capacity of displaced worker to accept retraining.

C-13c. Of those workers terminated (excluding retirees) due to the introduction of robots, how long will it take for them to obtain new, full-time employment?

	Median		
	1985	1990	1995
2 months or less	8%	9%	10%
2 - 6 months	25%	26%	27%
6 - 12 months	34%	35%	36%
1 - 2 years	17%	18%	18%
More than 2 years	8%	6%	2%
Will not find new full-time employment	8%	6%	7%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
2 months or less	5/10%	5/10%	5/15%
2 - 6 months	10/50%	5/40%	3/30%
6 - 12 months	10/40%	10/35%	5/30%
1 - 2 years	4/20%	0/20%	0/20%
More than 2 years	0/10%	0/10%	0/10%
Will not find new full-time employment	0/10%	0/10%	0/15%

Comments:

This also depends on person's willingness to relocate! This is probably a small number of people, especially in 1985.

Assumes healthy economy will learn to take advantage of new forms of automation and more flexibility of upcoming work force.

Hopefully, our overall economy will improve in the future.

S-13d. Of those workers terminated due to the introduction of robots and finding new full-time employment, how far will they have to relocate in order to obtain new employment?

	Median		
	1985	1990	1995
Less than 25 miles	66%	65%	63%
25 - 100 miles	20%	22%	25%
101 - 250 miles	3%	5%	6%
Over 250 miles	11%	8%	6%
	100%	100%	100%

	Interquartile Range		
	1985	1990	1995
Less than 25 miles	17/80%	17/75%	30/80%
25 - 100 miles	10/40%	10/35%	5/45%
101 - 250 miles	1/8%	2.5/20%	2.5/15%
Over 250 miles	5//15%	2.5/15%	2.5/10%

Comments:

There will be more opportunities as the robot field develops to find work closer to home.

There will be some stabilization in the present move to the south. New industrial areas will become mature.

S-14. On the average, in your own experience, what will be the number of workers typically displaced (see note on displacement in Question S-2) by a single robot of each type in a 2-shift operation?

	Median Number of Displaced Workers		
	1985	1990	1995
All industry, average	3	4	5
Machine tending	2	3	3
Material transfer (excl. machine tending)	2	3	4
Spot welding	3	4	4
Arc welding	3	3	4
Spray painting/coating	3	3	3
Processing (routing, drilling, grinding, etc.)	2	3	3
Electronics assembly	3	4	4
Other assembly	2	3	3
Inspection	2	2	3

	Interquartile Range Number of Displaced Workers		
	1985	1990	1995
All industry, average	2/4	3/4	4/5
Machine tending	2/4	2/4	2/4
Material transfer (excl. machine tending)	2/4	3/4	3/4
Spot welding	3/4	3/5	3/7
Arc welding	2/3	2/5	3/6
Spray painting/coating	2/3	2/4	2/5
Processing (routing, drilling, grinding, etc.)	2/3	2/4	2/6
Electronics assembly	3/4	3/4	3/5
Other assembly	1/3	2/5	2/7
Inspection	1/3	2/4	2/4

Comments:

Almost all effects will be minor.

Assume 15-person work group, initial real productivity gain of greater than 20%; assume increased productivity gain due to technological improvements by 1995.

Due to growth, these numbers may represent "the hiring" that may not have to be done now due to automation.

The newer robots will be able to handle a greater range of work.

S-15a. Among robot vendors, what will be the average required labor input in total man-hours, for the manufacture of one robot?

	Median		
	1985	1990	1995
Man-hours per robot:	500	400	390

	Interquartile Range		
	1985	1990	1995
Man-hours per robot:	400/1750	400/1600	300/1500

Comments:

Gains may be spectacular if and when it becomes cost-efficient to adopt more mass production techniques.

S-15b. For every 10 robots manufactured in the U.S., how many total jobs will be created in the industries supplying the robot producers?

	Median		
	1985	1990	1995
Supplier industries' jobs per 10 robots produced	2	2	3

	Interquartile Range		
	1985	1990	1995
Supplier industries' jobs per 10 robots produced	1/6	1/7	1/8

Comments:

Not enough to provide jobs for displaced workers.

S-16. According to the Bureau of the Census, in 1980, 84% of all surveyed workers declared themselves as "satisfied" with their jobs. What will this percentage of "satisfied" workers be in the future?

	Median Percentage of Workforce		
	1985	1990	1995
"Satisfied" workers	84%	85%	87%

	Interquartile Range Percentage of Workforce		
	1985	1990	1995
"Satisfied" workers	80/85%	80/87%	81/90%

Comments:

Change brings dissatisfaction to many people. However, by 1995 the social sciences will have been improved sufficiently by information science improvements to provide most people the knowledge that they are a right person in the right place for themselves.

This will not change much--it is a very subjective topic--more worker attitude regardless of job content.

Very little of the decrease will be due to robots as such. Most will be due to routine and/or high-pressure jobs connected with FMS's.

Will vary as function of unemployment rate.

S-17. In 1990, how would you rate the following worker attitudes in relation to today (1983)?

	Median
People will work:	SAME
Employee loyalty will be:	GREATER
Workmanship will be:	GREATER
Pride in work will be:	GREATER

	Interquartile Range
People will work:	Harder/Less Hard
Employee loyalty will be:	Greater/Same
Workmanship will be:	Greater/Greater
Pride in work will be:	Greater/Same

Comments:

As the "Robber Baron" mentality of the industrial period is replaced in the minds of management & labor alike by a "quality of work for quality of life" mind set, then the quality of that relationship and everything else will improve greatly.

This depends entirely on how smart management is in designing the jobs for humans. It could be significant in either direction.

We have no economic alternatives except to design work programs to accomplish those results.

S-18. Rank order (from 1 to 8) worker productivity in the countries listed below for the following years. (1 = highest worker productivity)

	Median Rank		
	1985	1990	1995
Canada	4	5	5
France	7	7	6
Italy	8	8	8
Japan	1	1	1
Korea	5	4	4
U.K.	6	6	7
U.S.	2	2	2
West Germany	3	3	3

S-19. When robots become implemented in typical U.S. factories at significant levels, how many (8-hour) shifts will a "typical" robot operate per week, by industry?

	Median Shifts per Week		
	1985	1990	1995
Agriculture	5	5	5
Mining and extractive	5	5	5
Construction	5	5	5
Electricity generation	10	15	15
Consumer non-durables	5	10	10
Non-metal primary commodities	7	10	10
Primary metals	7	10	10
Non-metal fabricated commodities	5	10	10
Fabricated metal products	10	10	10
Machinery	10	10	10
Electronics and precision equipment	10	10	10
Automotive	10	15	15
Aerospace	10	10	10
Other transportation equipment	5	10	10

	Interquartile Range Shifts per Week 1985	1990	1995
Agriculture	5/5	5/5	5/10
Mining and extractive	2/10	3/10	3/10
Construction	5/5	5/5	5/5
Electricity generation	5/15	5/15	10/15
Consumer non-durables	5/10	5/10	10/10
Non-metal primary commodities	5/10	10/10	10/10
Primary metals	5/10	7/10	7/15
Non-metal fabricated commodities	5/10	10/10	10/15
Fabricated metal products	5/10	10/10	10/15
Machinery	10/10	10/10	10/15
Electronics and precision equipment	5/10	10/14	10/14
Automotive	10/15	10/15	10/15
Aerospace	5/10	10/10	10/10
Other transportation equipment	5/10	10/12	10/15

Comments:

Every industry will push to achieve 24-hour production where possible, and simultaneously reduce the number of producing units to prevent serious overproduction.

Assuming a need for two shifts to achieve an acceptable ROI

Depends on demand for products.

S-20a. Rank order (from 1 to 10) the potential effectiveness of the following incentives to gain union acceptance of the installation of robots. (1 = most effective)

	Median Rank 1985	1990	1995
1. Retraining provisions	2	2	2
2. Increased paid personal holidays	7	7	7
3. Reduced work week at no loss of income	4	4	4
4. Advance notice of technological changes	5	5	5
5. Sharing of productivity benefits	3	3	3
6. Supplemental unemployment benefits	6	6	6
7. Increased severance pay	8	8	8
8. Payment of union dues by robots	9	9	9
9. Guaranteed continued employment	1	1	1

	Interquartile Range Rank		
	1985	1990	1995
1. Retraining provisions	2/2	2/3	2/3
2. Increased paid personal holidays	6/8	5/8	5/8
3. Reduced work week at no loss of income	3/5	3/5	2/5
4. Advance notice of technological changes	3/5	3/6	3/6
5. Sharing of productivity benefits	3/4	2/4	3/4
6. Supplemental unemployment benefits	5/7	5/7	5/7
7. Increased severance pay	6/8	6/8	7/8
8. Payment of union dues by robots	9/9	9/9	9/9
9. Guaranteed continued employment	1/1	1/1	1/1

Comments:

"3" and "5" are essentially the same thing. Re "4" - they see it coming as clearly as we do. Re "8" - most unions will see this as impractical.

By 1990-1995 we will be entering a period of relative labor shortage.

The unions will strive for whatever: a) protects the union management and jobs, b) protects the union management's pocketbook, c) keeps the largest number of people within their union organization.

"Guaranteed continued employment" is number one. Without some statement of intent from the company to provide job security, unions and the rank and file will fight the implementation of widespread robotics.

S-20b. Rank order (from 1 to 10) the likelihood of actual implementation of the following incentives to gain union acceptance of the installation of robots. (1 = most likely)

	Median Rank		
	1985	1990	1995
1. Retraining provisions	1	1	1
2. Increased paid personal holidays	7	8	8
3. Reduced work week at no loss of income	8	7	7
4. Advance notice of technological changes	2	2	2
5. Sharing of productivity benefits	4	3	3
6. Supplemental unemployment benefits	3	4	4
7. Increased severance pay	5	5	5
8. Payment of union dues by robots	9	9	9
9. Guaranteed continued employment	6	6	6

		Interquartile Range Rank		
		1985	1990	1995
1.	Retraining provisions	1/2	1/1	1/1
2.	Increased paid personal holidays	5/8	5/8	5/8
3.	Reduced work week at no loss of income	6/8	5/8	4/8
4.	Advance notice of technological changes	2/3	2/2	2/2
5.	Sharing of productivity benefits	3/7	3/5	3/5
6.	Supplemental unemployment benefits	4/5	4/6	4/6
7.	Increased severance pay	3/7	3/7	3/7
8.	Payment of union dues by robots	9/9	9/9	9/9
9.	Guaranteed continued employment	3/6	4/7	4/8

Comments:

The rank order wil. stay essentially the same, but as time passes, it will become more likely that the line items will have been implemented.

By 1995, unions will have probably had to learn the hard way.

As long as unions continue their reactive and self-protectionist mind-set, they will remain post-industrial in their behavior, and will not change from one decade to the next.

S-21. When robots become implemented in typical U.S. factories at significant levels, what will be the average productivity gain directly attributable to the use of robots, by type of robot?

	Median Percent Productivity Gain		
	1985	1990	1995
Machine tending	20%	25%	30%
Material transfer (excl. machine tending)	25%	30%	35%
Spot welding	25%	30%	40%
Arc welding	20%	25%	30%
Spray painting/coating	25%	30%	40%
Processing (routing, drilling, grinding, etc.)	10%	20%	30%
Electronics assembly	20%	25%	30%
Other assembly	15%	20%	25%
Inspection	10%	20%	25%

	Interquartile Range		
	Percent Productivity Gain		
	1985	1990	1995
Machine tending	15/25%	20/40%	20/45%
Material transfer (excl. machine tending)	15/25%	20/35%	20/40%
Spot welding	25/50%	25/40%	30/70%
Arc welding	20/40%	25/40%	30/45%
Spray painting/coating	20/40%	30/40%	35/40%
Processing (routing, drilling, grinding, etc.)	10/25%	15/25%	25/30%
Electronics assembly	15/40%	25/45%	30/50%
Other assembly	10/35%	15/40%	20/50%
Inspection	10/25%	15/35%	20/50%

Comments:

It will be "recognized" as being most significant in those areas where the consumer-general public most notices change; i.e. in painting and finishing and processing. Other productivity may even be greater but will be less attended to and noticed.

But only for those jobs in which robots are used, not for overall plant.

I think the greatest gains to be achieved with robotics are in the area of quality; productivity gains are a subset of that.

S-22a. Rank the near-term (i.e., 1985) degree of importance of previous acquisition of each of the following skills toward the successful training of a robotics maintenance worker. (1 = Critical; 5 = Not Important)

	Median
	1985
General mechanical skills	2
Knowledge of hydraulic valves	3
General electrical skills	2
Electronics skills	1
Programming skills	3
Knowledge of numerical controls	2
General preventive maintenance	2

	Interquartile Range
	1985
General mechanical skills	1/2
Knowledge of hydraulic valves	2/3
General electrical skills	1/2
Electronics skills	1/2
Programming skills	2/4
Knowledge of numerical controls	2/3
General preventive maintenance	2/3

Comments:

Because of the advent of robotics, solid understanding of the basic and advanced technologies of automation are needed to help the worker or potential worker to handle the drastic concept level change required of the typical maintenance person.

S-22b. Rank the degree of importance of the previous acquisition of each of the following skills toward the successful training of a robotics maintenance worker in 1990.

	Median
	1990
General mechanical skills	2
Knowledge of hydraulic valves	3
General electrical skills	2
Electronics skills	1
Programming skills	2
Knowledge of numerical controls	2
General preventive maintenance	2

	Interquartile Range
	1990
General mechanical skills	1/2
Knowledge of hydraulic valves	2/3
General electrical skills	1/2
Electronics skills	1/2
Programming skills	2/3
Knowledge of numerical controls	2/3
General preventive maintenance	1/3

Comments: (None)

S-23a. What will be the distribution of highest educational attainment of the work force of the future?

Median

	Percent of Workforce			
	Actual 1980	1985	1990	1995
No high school diploma	22.6%	20%	16%	13%
High school diploma	40.2%	40%	40%	39%
Some college, no degree	18.1%	20%	21%	24%
Bachelor's degree	11.0%	12%	14%	14%
Advanced study	8.1%	8%	9%	10%

Interquartile Range

	Percent of Workforce			
	Actual 1980	1985	1990	1995
No high school diploma	22.6%	19/21%	15/20%	10/15%
High school diploma	40.2%	38/42%	38/44%	33/45%
Some college, no degree	18.1%	19/20%	20/25%	20/28%
Bachelor's degree	11.0%	11/14%	11/15%	13/20%
Advanced study	8.1%	8/10%	7/10%	8/12%

Comments:

High school diplomas will subdivide into being certificates of attendance and certifications of skill levels after 1990.

S-23b. Of all industrial robots in operation in each of the following years, how will they be distributed geographically?

		Median	
	1985	1990	1995
New England (ME, NH, VT, MA, RI, CT)	10%	11%	11
Mid-Atlantic (NY, PA, NJ)	10%	11%	10%
South Atlantic (DE, MD, DC, VA, WV, NC, SC, GA, FL)	8%	9%	9%
East North Central (OH, MI, IN, IL, WI)	40%	34%	28%
West North Central (MN, IA, MO, ND, SD, NE, KS)	5%	5%	6%
East South Central (KY, TN, MS, AL)	5%	5%	6%
West South Central (AR, LA, OK, TX)	5%	5%	7%
Mountain (MT, WY, CO, NM, ID, UT, AZ, NV)	5%	5%	6%
Pacific (CA, OR, WA, AK, HI)	12%	15%	17%
	100%	100%	100%

		Interquartile Range	
	1985	1990	1995
New England (ME, NH, VT, MA, RI, CT)	5/11%	5/11%	5/11%
Mid-Atlantic (NY, PA, NJ)	8/15%	5/12%	5/10%
South Atlantic (DE, MD, DC, VA, WV, NC, SC, GA, FL)	5/10%	5/14%	5/15%
East North Central (OH, MI, IN, IL, WI)	17/50%	20/40%	20/40%
West North Central (MN, IA, MO, ND, SD, NE, KS)	2/6%	3/8%	4/10%
East South Central (KY, TN, MS, AL)	3/5%	3/5%	5/7%
West South Central (AR, LA, OK, TX)	5/10%	5/10%	5/10%
Mountain (MT, WY, CO, NM, ID, UT, AZ, NV)	2/5%	2/8%	4/8%
Pacific (CA, OR, WA, AK, HI)	8/17%	10/16%	10/17%

Comments: (None)

S-24. General Motors has estimated that, for every 10 of its robots, it will require 3 full-time maintenance workers. Other estimates have ranged from 1 to as many as 15 maintenance workers for every 10 robots. What are your estimates for workers per 10 robots in each of the following years?

		Median	
	1985	1990	1995
All Industry, Average	3	3	2

	Interquartile Rank		
	1985	1990	1995
All Industry, Average	2/3	2/3	2/3

Comments:

Depends especially on number of shifts of operation but also on type of robot, application, workplace conditions, etc. Welding and painting robots that dominate in the auto industry probably require more MX than any other applications.

Reliability and serviceability improvements.

Depends on degree of training.

You can gain economies of scale and other benefits with higher quantities, and new skill levels.

Maintenance.

S-25. For every 10 robots, how many full-time programmers will be required, on the average?

	Median		
	1985	1990	1995
All Industry, Average	2	1	1

	Interquartile Range		
	1985	1990	1995
All Industry, Average	1/2	1/2	1/1

Comments:

Depends on how robots are used.

Depends on line changes required for product.

More robots of same program and ease in programming (higher level "language" or "no" language).

Programmers and operators will increasingly be same people.

Programming is not a separately identifiable occupation in user industries currently. With the development of more flexible operations and off-line control from a central station, programming may become more important, but it is difficult to foresee when it will occur.

Programming will be performed by set-up or maintenance personnel.

This will depend mostly on the frequency at which the production line is changed, products re-designed, etc.

There are not now nor will there ever be 2 full-time programmers per 10 robots--this is primarily an installation and setup function.

S-26. In what ways will manned work stations be redesigned as a direct result of the implementation of robotics technology?

Response	% of All Responses
Material transport	15%
Improved layout	12
Utilizing robots as co-worker	12
Better tools/fixtures	7
Safety	7
Higher productivity	7
Greater use of computer and electronics	7
Separation of robots and workers	4
More mentally demanding jobs	4
Storage	4
Ergonomics	4
Voice dialogue	4
Greater space requirements	4
Less attractive work environments	4
TV monitoring	4
	100%

Comments: (None)

S-27. The following set of questions is designed to forecast robot trends by individual robot types. We realize that to answer all the questions in the set (S-27a through S-27i) would be a substantial undertaking. Thus, we ask that you provide answers for ONLY THOSE ROBOT APPLICATIONS that you feel your expertise allows. Thanks.

S-27a. Of all material transfer robots (excluding machine tending units) purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	6%	8%	12%
Direct Labor Productivity	56%	56%	55%
Indirect Labor Productivity	11%	12%	12%
Energy Savings	1%	2%	2%
Material Waste Reduction	6%	6%	6%
Less Floor Space	2%	1%	0%
Inventory Reduction	9%	8%	6%
Simplified Management	3%	1%	1%
Worker Safety	6%	6%	6%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	2/20%	5/20%	5/20%
Direct Labor Productivity	30/60%	35/70%	26/70%
Indirect Labor Productivity	2/16%	0/16%	5/15%
Energy Savings	0/5%	0/5%	0/5%
Material Waste Reduction	0/10%	0/10%	1/10%
Less Floor Space	0/5%	0/5%	0/4%
Inventory Reduction	0/13%	5/10%	5/10%
Simplified Management	0/5%	0/5%	0/5%
Worker Safety	2/8/%	2/10%	1/10%
Other	0/0%	0/0%	0/0%

Comments:
Expect general profile would hold fairly constant.

S-27b. Of all spot welding robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median Percent of Total Savings		
	1985	1990	1995
Product Quality	32%	24%	18%
Direct Labor Productivity	50%	58%	60%
Indirect Labor Productivity	6%	6%	6%
Energy Savings	0%	0%	0%
Material Waste Reduction	6%	6%	6%
Less Floor Space	0%	0%	0%
Inventory Reduction	6%	6%	10%
Simplified Management	0%	0%	0%
Worker Safety	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Total Savings		
	1985	1990	1995
Product Quality	10/25%	10/25%	15/35%
Direct Labor Productivity	40/50%	30/70%	30/70%
Indirect Labor Productivity	5/10%	5/15%	5/20%
Energy Savings	0/2%	0/2%	0/2%
Material Waste Reduction	2/10%	2/8%	2/8%
Less Floor Space	0/3%	0/3%	0/3%
Inventory Reduction	5/15%	5/15%	5/15%
Simplified Management	0/0%	0/0%	0/0%
Worker Safety	0/5%	0/5%	0/5%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-27c. Of all arc welding robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	15%	24%	27%
Direct Labor Productivity	62%	58%	54%
Indirect Labor Productivity	8%	6%	5%
Energy Savings	0%	0%	0%
Material Waste Reduction	8%	6%	5%
Less Floor Space	0%	0%	0%
Inventory Reduction	7%	6%	9%
Simplified Management	0%	0%	0%
Worker Safety	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	10/25%	10/25%	15/35%
Direct Labor Productivity	40/75%	30/75%	20/60%
Indirect Labor Productivity	0/10%	0/15%	0/20%
Energy Savings	0/5%	0/5%	0/5%
Material Waste Reduction	0/10%	0/9%	0/5%
Less Floor Space	0/10%	0/10%	0/10%
Inventory Reduction	5/10%	5/20%	5/25%
Simplified Management	0/0%	0/0%	0/0%
Worker Safety	0/5%	0/5%	0/5%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-27d. Of all spray painting robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	34%	32%	28%
Direct Labor Productivity	40%	38%	34%
Indirect Labor Productivity	6%	6%	6%
Energy Savings	2%	0%	6%
Material Waste Reduction	11%	11%	11%
Less Floor Space	0%	0%	0%
Inventory Reduction	1%	7%	9%
Simplified Management	0%	0%	0%
Worker Safety	6%	6%	6%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	15/35%	15/35%	15/35%
Direct Labor Productivity	30/40%	30/50%	20/50%
Indirect Labor Productivity	0/10%	0/10%	0/20%
Energy Savings	0/10%	0/5%	0/10%
Material Waste Reduction	10/20%	5/15%	5/20%
Less Floor Space	0/0%	0/3%	0/3%
Inventory Reduction	0/10%	0/15%	0/10%
Simplified Management	0/0%	0/2%	0/0%
Worker Safety	5/10%	0/20%	0/10%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-27e. Of all processing (e.g., routing, grinding, drilling, etc.) robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median Percent of Total Savings		
	1985	1990	1995
Product Quality	18%	19%	21%
Direct Labor Productivity	50%	50%	50%
Indirect Labor Productivity	6%	6%	7%
Energy Savings	2%	3%	3%
Material Waste Reduction	12%	10%	7%
Less Floor Space	0%	0%	0%
Inventory Reduction	6%	6%	6%
Simplified Management	0%	0%	0%
Worker Safety	6%	6%	6%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Total Savings		
	1985	1990	1995
Product Quality	10/35%	10/30%	10/40%
Direct Labor Productivity	20/55%	30/55%	30/70%
Indirect Labor Productivity	2/10%	2/10%	2/10%
Energy Savings	0/10%	0/5%	0/5%
Material Waste Reduction	3/15%	2/20%	0/10%
Less Floor Space	0/5%	0/5%	0/5%
Inventory Reduction	5/10%	5/10%	5/9%
Simplified Management	0/0%	0/0%	0/3%
Worker Safety	0/10%	0/9%	0/8%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-27f. Of all electronics assembly robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median Percent of Total Savings		
	1985	1990	1995
Product Quality	38%	34%	32%
Direct Labor Productivity	38%	40%	41%
Indirect Labor Productivity	6%	5%	5%
Energy Savings	0%	0%	0%
Material Waste Reduction	6%	11%	11%
Less Floor Space	0%	0%	0%
Inventory Reduction	6%	5%	5%
Simplified Management	6%	5%	5%
Worker Safety	0%	0%	1%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Total Savings		
	1985	1990	1995
Product Quality	10/40%	10/40%	20/40%
Direct Labor Productivity	25/50%	22/55%	20/60%
Indirect Labor Productivity	0/7%	0/10%	4/5%
Energy Savings	0/2%	0/4%	0/5%
Material Waste Reduction	4/10%	2/15%	1/20%
Less Floor Space	0/2%	0/4%	0/4%
Inventory Reduction	0/10%	0/5%	0/5%
Simplified Management	0/8%	0/7%	0/7%
Worker Safety	0/5%	0/5%	0/5%
Other	0/0%	0/0%	0/0%

Comments:

Expect general profile would hold fairly constant.

Much of the savings attributed to direct labor productivity, material waste reduction, and inventory reduction really should be included in the contribution to savings represented by product quality.

S-27g. Of all other assembly robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median Percent of Total Savings		
	1985	1990	1995
Product Quality	26%	21%	13%
Direct Labor Productivity	41%	44%	47%
Indirect Labor Productivity	13%	13%	13%
Energy Savings	0%	0%	0%
Material Waste Reduction	5%	5%	7%
Less Floor Space	0%	0%	0%
Inventory Reduction	6%	9%	13%
Simplified Management	6%	5%	4%
Worker Safety	3%	3%	3%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Total Savings		
	1985	1990	1995
Product Quality	8/30%	9/20%	10/20%
Direct Labor Productivity	30/60%	30/55%	30/70%
Indirect Labor Productivity	1/18%	1/15%	4/20%
Energy Savings	0/1%	0/0%	0/0%
Material Waste Reduction	2/10%	2/10%	1/10%
Less Floor Space	0/3%	0/3%	0/3%
Inventory Reduction	0/15%	0/10%	5/15%
Simplified Management	2/10%	2/10%	2/5%
Worker Safety	0/3%	0/3%	0/5%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-27h. Of all inspection robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Median		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	36%	38%	38%
Direct Labor Productivity	55%	51%	46%
Indirect Labor Productivity	9%	7%	8%
Energy Savings	0%	0%	0%
Material Waste Reduction	0%	4%	8%
Less Floor Space	0%	0%	0%
Inventory Reduction	0%	0%	0%
Simplified Management	0%	0%	0%
Worker Safety	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range		
	Percent of Total Savings		
	1985	1990	1995
Product Quality	20/40%	10/50%	15/35%
Direct Labor Productivity	25/70%	30/60%	25/60%
Indirect Labor Productivity	0/10%	0/10%	1/10%
Energy Savings	0/0%	0/0%	0/1%
Material Waste Reduction	0/1%	0/5%	0/10%
Less Floor Space	0/1%	0/3%	0/3%
Inventory Reduction	0/5%	0/10%	0/10%
Simplified Management	0/1%	0/0%	0/5%
Worker Safety	0/0%	0/0%	0/0%
Other	0/0%	0/0%	0/0%

Comments:

Expect general profile would hold fairly constant.

S-27i. Of all machine-tending robots purchased in the U.S. in each of the following years, what will be the percentage breakdown of total savings represented by each of the following factors?

	Percent of Total Savings		
	1985	1990	1995
Product Quality	6%	9%	15%
Direct Labor Productivity	93%	86%	74%
Indirect Labor Productivity	1%	1%	1%
Energy Savings	0%	0%	0%
Material Waste Reduction	0%	0%	0%
Less Floor Space	0%	0%	0%
Inventory Reduction	0%	4%	10%
Simplified Management	0%	0%	0%
Worker Safety	0%	0%	0%
Other	0%	0%	0%
	100%	100%	100%

	Interquartile Range Percent of Total Savings		
	1985	1990	1995
Product Quality	2/10%	0/10%	2/15%
Direct Labor Productivity	60/95%	50/90%	40/80%
Indirect Labor Productivity	0/10%	0/1%	0/5%
Energy Savings	0/0%	0/0%	0/0%
Material Waste Reduction	0/10%	0/10%	0/10%
Less Floor Space	0/0%	0/0%	0/0%
Inventory Reduction	0/10%	0/15%	0/20%
Simplified Management	0/0%	0/0%	0/1%
Worker Safety	0/0%	0/0%	0/0%
Other	0/0%	0/0%	0/0%

Comments: (None)

S-28. My company is:

User of robots:	75% Yes	25% No
Manufacturer of robots:	17% Yes	83% No

APPENDIX B

DELPHI FORECASTING METHOD

This comprehensive forecast was created using Delphi techniques. Delphi is a systematic, iterative method for forecasting based on independent inputs from a group of experts. Its objective is to obtain a consensus of opinion from the panel of experts regarding future events. In practice, forecasts or estimates of long-term future scenarios may be derived using numerous methods, including intuitive forecasts, trend extrapolation, trend correlation analysis, and analogy techniques.

Like other intuitive forecasting processes, such as a poll, committee, or panel consensus, the Delphi method relies on the judgment of knowledgeable experts. One of its values is derived from realizing that future projections, on which decisions regarding policy must rely, are strongly influenced by personal preferences and expectations, in addition to more quantitative factors.

For events on which long-range forecasting can be effective, the Delphi's tightly structured and iterative polling technique among a group of experts holds great promise. We believe that for the vast majority of future events, the group consensus enjoys a higher probability of proving accurate than the prediction of a single person.

Because a single person is not likely to be expert on all issues, there is a higher likelihood that from the Delphi group, an expert (or experts) will be available for every issue we have addressed.

When making long-range forecasts on events for which a suitable data base does not exist to permit model building or logical extrapolation, few alternatives are left but to solicit learned opinion.

For most applications, it is well accepted that opinion gleaned from several experts is superior to the opinion of just one expert. Studies have demonstrated that the estimation error of a group will be less than the average error the predictions of individuals. However, users of the Delphi method must design procedures to achieve the maximum dynamic performance of the group of experts so as to enhance the validity of their group opinions.

Rand studies and psychological analyses have demonstrated the inherent dangers of opinions derived from a group with members working on a face-to-face basis. Dalkey of Rand summarized these pitfalls as follows.[1]

> The traditional way of polling individual opinions is by face-to-face discussion. Numerous studies by psychologists in the past two decades have demonstrated some serious difficulties with face-to-face interaction. Among the most serious are: (1) Influence of dominant individuals. The group opinion is highly influenced, for example, by the person who talks the most. There is very little correlation between pressure of speech and knowledge. (2) Noise. By noise is not meant auditory level (although in some face-to-face situations this may be serious enough) but semantic noise. Much of the "communication" in a discussion group has to do with individual and group interests, not with problem solving. This kind of communication, although it may appear problem-oriented, is often irrelevant or biasing. (3) Group pressure for conformity. In experiments at Rand and elsewhere, it has turned out that, after face-to-face discussions, more often than not the group response is less accurate than a simple median of individual estimates without discussion.

One of the many Delphi strengths is that it retains the valuable aspects of group communication in moving toward a consensus opinion, but avoids personal interaction pitfalls.

Delphi replaces direct open debate by a carefully designed program of interrogation. Delphi seeks controlled elicitation of group opinion and commentary by an iterative use of questionnaires with a selective feedback of previous group responses as an informational basis for subsequent forecasts by the expert panelists of the events under consideration. Three features characterize the Delphi procedure and distinguish it from the usual methods of group interactions: anonymous interaction, iteration with controlled statistical and commentary feedback, and statistical group response.

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[1] Norman C. Dalkey, "The Delphi Method; An Experimental Study of Group Opinion." Memorandum RM-5888 PR (Santa Monica, CA: Rand Corporation, 1969), p. 14.

While conducting a Delphi survey, the identities of panelists are not made known to each other. Futhermore, the responses of the participants remain completely anonymous to avoid the possibility of attaching a specific opinion to a particular individual. Among other advantages, this enables any member of the Delphi community to comfortably revise previous forecasts as new evidence is submitted by other panelists during future rounds of questioning. Most important, it allows any ideas to be considered on merits without regard for the presumed genius or the real or imagined status of the originator.

The opinions of the group members are obtained from responses to a questionnaire. Several rounds may be required to arrive at a consensus. The coordinator of the forecast extracts the relevant information from the returned questionnaires and submits the statistical compilation and commentary to the panel for future questionnaire rounds. Influences of personal objectives such as winning an argument are eliminated, and the original goals of the study remain the primary concern. Written comments substantiating a forecaster's position relative to each question are fundamental in the process in creating the convergence of the group's opinions while moving toward a consensus.

It is the nature of other intuitive forecasting methods to fabricate a majority opinion, giving little if any notice to the minority viewpoints. The Delphi technique offers both a statistical and commentary response which encompasses and highlights the ideas of the entire group. Usually the group response to a single question is presented in terms of a median and interquartile range (IQR).[2] This representation of results denotes the middle opinion and, more importantly, the spread and the central tendency of the group's ideas. A powerful feature of Delphi is that comments supporting actions divergent from the group's developing consensus are included in the commentary returned to the panelists as a means of persuading other panelists that the nonconforming forecast is more valid.

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[2] The median is obtained by arranging all replies in a chronological list and selecting the middle value. The interquartile range is specified by the two extremes of the middle 50% of the same chronological list used to obtain the median.

APPENDIX C

GLOSSARY

Adaptive Control: A control method in which control parameters are continuously and automatically adjusted in response to measured process variables to achieve near-optimum performance.

Articulated, a.k.a. "joint spherical" and/or "joint arm:" These robots have rotary joints in several places along the arm that roughly correspond to the shoulder, elbow, and wrist in humans. They, too, are usually mounted on a rotary base.

Bin Picking: (Also known as the occlusion problem.) The ability to remove individual parts from a bin in an oriented fashion.

Cartesian, a.k.a. "rectilinear-coordinate:" These robots are mounted on a fixed base. All arm motions of the manipulator are in a straight line, either in-out, up-down, or side-to-side. Even though a pivoting wrist joint may be provided, the work envelope of these robots conforms to either a cube or a rectangular solid.

Continuous Path: In contrast to point-to-point, a robot which is controlled over the entire path traversed. An example is a spray painting robot. The end points are relatively unimportant since they are outside the dimensions of the object being painted, while the trajectory of the painting itself is crucial.

Cylindrical: The manipulator is usually a vertical column with a horizontal arm mounted on a rotating base. The volume of space the end-of-arm tooling can occupy is basically a portion of a cylinder.

Feedback Sensing: A mechanism through which information from sensing devices is fed back into the robot's control unit. The information is utilized in the subsequent direction of the robot's motion.

Intelligent: The ability of a robot to perform functions that are normally associated with human intelligence, such as reasoning, planning, problem-solving, pattern recognition, perception, cognition, understanding, and learning.

Leading from Point-to-Point: A method of "teaching" whereby a human operator leads the robot through all steps of the operation, recording in memory only the attitude and position of its limbs at the start and the end of the move.

A majority of the definitions in this glossary were adapted from ICAM Robotics Guide, U.S. Air Force Technical Document AFWAL-TR-80-4042, Volume II, April 1980.

Modular: Made up of subunits which can be combined in various ways. In robotics, a robot constructed from a number of interchangeable subunits, each of which can be one of a range of sizes or have one of several possible motion styles (prismatic, cylindrical, etc.) and number of axes. Modular design permits assembly of products, software, or hardware from standardized components.

Off-line Programming Language Teaching: This method of "teaching" the robot involves control and positioning through a computer program. It is only relevant for programmable robots. Coordinates for positions and attitude of limbs are preset by the program so that the robot is not required to be led through motions.

Pattern Recognition: Description, classification of pictures or other data structures into a set of categories. It usually involves an algorithm for analyzing camera scenes. Identification of objects is accomplished by determining specific characteristics of the given object and comparing them to the corresponding characteristics of a prototype.

Pendant Control: A control panel mounted on a pendant cable enables the human operator to stand in the most favorable position to observe, control, and record the desired movements in the robot's memory.

Pick and Place: A simple robot, often with just two or three degrees of freedom, that transfers items from place to place by means of point-to-point moves. Little or no trajectory control is available. This type is often referred to as a "bang-bang" robot.

Point-to-Point: A control scheme in which the inputs or commands specify a limited number of points along a desired path of motion. The control system determines the intervening path segments in rote fashion.

Programmable: Capable of being instructed to operate in a specific manner, or of accepting set points or other commands from a remote source.

Scene Analysis: The ability of a camera-equipped robot to recognize an arbitrary object placed in an arbitrary scene.

Special: Usually a custom-built robot. This is in contrast to a modular robot made up of standardized units.

Spherical: Mounted on a rotary base and resembling the turret of a tank, the arm cannot only extend and retract, but is pivoted so it can swing vertically, allowing rotary motion about a horizontal plane. The end effector moves in a volume of space that is a portion of a sphere.

Tactile Sensors: Sensors which respond to contact forces that arise between themselves and solid objects. The object must actually be touched, unlike proximity sensors. Tactile sensors can be classified into two groups: touch sensors and stress sensors. Touch sensors indicate contact; stress sensors indicate the magnitude of the contact forces. The most common touch sensor is the micro-switch, while the most common stress sensor is the strain gage.

Vision Capability: Robot vision involves the capability of making a pictorial representation of a particular object, then analyzing the picture through a computer algorithm. It is currently rudimentary, though it is successful at black on white and with objects in consistent orientation patterns.